ENDEAVOUR

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The drawing on the cover is of the bark Endeavour, *which,
commanded by Captain James Cook and carrying a number of
scientific workers, was sent out by the British Admiralty in 1768
to chart the South Pacific Ocean and observe the transit of Venus*

CONTENTS

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The conservation of museum objects

'A thing of beauty is a joy for ever: Its loveliness increases; it will never Pass into nothingness'. So sang the poet, truthfully in the sense he intended —but he was not the curator of a museum or art gallery. Interpreted with prosaic literalness, the assertion is diametrically opposed to the truth. Curators know only too well that tapestries fade or are devoured by moths; that paintings blacken; that illuminated manuscripts become brittle and fragile; and that palimpsests grow more and more illegible. In bygone days a melancholy resignation accepted such decay as inevitable, and did not do—indeed could not do—very much to prevent it.

Our own outlook is more hopeful. We realize that, whenever a collection of precious material is assembled in a museum or gallery, we have more considerations than those of historical research, documentation, public exhibitions, lectures, and so forth. There are also fundamental problems of a scientific and technical nature, which perhaps we have come to perceive through the success of science in solving similar problems in other fields. They concern the rational care of artistic treasure, anticipating wherever possible the causes of deterioration, devising methods of preventing it, and, where decay has already set in, restoring as nearly as may be to a condition acceptable and permanent. Stated thus, the problems clearly demand scientists for their solution, but it is not suggested that the duty of conservation can be adequately performed without reference to aesthetic criteria. On the contrary, such criteria must be continually to the fore; yet scientists have a perfectly defined task—namely to understand the 'mechanics' and to reason from them objectively.

This is not the occasion on which to enter into a discussion of the details of procedure, though the first term of reference must obviously be the structures of the objects to be conserved. Equally important is the influence of environment. In this connection it may be observed that experience of wartime repositories, with their attendant risks and sometimes unpredictable circumstances, proved conclusively the value of air-conditioning and the beneficial effects it has in prolonging the life of works of art. It cannot heal the lesions of the past, but it can do much to eliminate their causes, and thus to prevent their repetition.

In conservation, as in other matters, apparatus and all types of instrumentation are relatively useless without a well trained and competent staff, at every level. Nevertheless, until very recently, no world-wide body existed to establish professional standards and to encourage first-class quality, both in knowledge of materials and in technical ability. However, in the spring of this year (1950) the International Institute for the Conservation of Museum Objects was founded in London, the first attempt ever made to set up a corporation of fellows and associates—elected with great care—to deal with the problems of the well-being of all kinds of precious things. In the course of time, the new institute should take its place with the well-known professional organizations— e.g. of architects, engineers, physicists, chemists, and so forth—brought into being for the same general purpose, namely to raise the status of specialists, and to maintain, and indeed require, high standards.

A feature of this new venture is its international character. Obviously, it could scarcely be otherwise, having regard to the wide distribution of museum objects. Its founders, leading authorities on the theory and practice of conservation, have received many tokens of encouragement, but none, so far, to compare with the generosity of the Nuffield Foundation, which has promised the institute £500 every year for five years. From the United States (where the project was originally

conceived), and from Belgium, financial aid has also been forthcoming, as well as from Britain in addition to the Nuffield gift. Like many another young enterprise, the new institute begins life with very modest means, and much of its work must necessarily be done as a labour of love. At the same time, it is much to be desired that its intentions should be widely known.

Nobody can view the present position with regard to the training and recruitment of conservators and restorers without grave misgivings. Admirable work is being done by individuals and institutions, academic and otherwise. Nevertheless, the need remains to combine just the right amount and type of scientific instruction and practical demonstration with due appreciation of the historical and aesthetic problems involved. At the Fogg Museum of Art at Harvard much has been, and is being, done. In London, at the Courtauld Institute, classes are in progress, and a refresher course for curators was tried this summer as an experiment, which it is hoped will justify itself and may become an annual event.

What, however, is required over and above all this, is a scheme of training applicable to every kind of museum object, and one which might in time acquire international recognition. Without the least desire, or indeed ability, to dictate, the new institute is empowered to grant diplomas when conditions permit, and it will try to inaugurate training schemes whenever and wherever it seems feasible to do so.

Lord Rutherford used to say that knowledge proceeds by the development of technique. True as this is, it needs the means of dissemination among all classes of interested persons. Until 1942, this was to a large extent achieved in these matters by the quarterly journal *Technical Studies in the Field of the Fine Arts*, published at Harvard under the editorship of G. L. Stout, who has been elected the first president of the new institute. The war brought about the demise of this distinguished periodical, since when the scientific and technical workers concerned have possessed no medium through which to make their investigations known. It is intended, as soon as possible, to remedy this misfortune by issuing a new publication under the aegis of the institute, and provisional arrangements are already in hand. Appearance of the journal at regular intervals will not be possible; the plan is for an issue to be produced whenever enough material of high quality has been collected to fill it. Meanwhile, a somewhat slighter bulletin is envisaged, to be circulated regularly and more frequently, to keep members informed of the institute's policy and activities.

Machinery for consultation and advice will be evolved gradually, so that co-operation with other bodies working in neighbouring fields of activity may be facilitated.

Such, in brief, is the skeleton of an organization to put the profession of conservation upon a more solid foundation than hitherto. Only time can show what the result will be, but the attempt itself is certainly not without significance. A broad generalization will perhaps illustrate this fact. In the important special case of the cleaning of pictures there is room, as is well known, for more than one school of thought and practice. Everybody who has had experience in this most difficult and delicate of tasks will agree that the skill of the restorer is a paramount consideration. Without it, knowledge of solvents, friction, paint-physics, molecular films, and all the rest may well be almost valueless. The same goes without saying with regard to integrity of purpose, and the will to co-operate with all others scientifically and technically qualified, in order that consultation may be effective and risks correspondingly reduced.

In the present state of knowledge, there can be no hard-and-fast rules, for the materials in question and their relationships to each other are too diverse, yet sensibility of observation combined with an objective approach should go far to overcome many of the obstacles encountered in the course of conservation and treatment.

The whole subject is, in fact, a study in very sensitive adjustment—to seek out the position of equilibrium between the use of empirical means, and that of rigorous scientific methods which must, by their very nature, act in a certain way and in no other.

The physics of the deformation of metals

E. N. DA C. ANDRADE

The systematic study of metals is particularly difficult because many different structures are possible under identical conditions and the mechanical properties are largely determined by small local irregularities in the crystal lattice. Investigations carried out with metals in single crystal form have done much to reveal the essentials of the problems of deformation. As regards polycrystalline metals, one phenomenon which has lately come into prominence is that of creep, that is, the slow flow under high stress. Here certain general laws have been established and interesting prospects revealed, which are now engaging the attention of both academic and industrial men of science. This article describes some recent work.

One of the paradoxes which physics presents to the uninitiated is that the mechanical properties of the gaseous state, which cannot be ordinarily seen, or handled except in closed vessels, are so much easier to explain than those of the condensed—that is, solid or liquid—state, which is visible, palpable, and readily accessible to a variety of simple tests. The reason for this is, of course, that in the gaseous state the molecules are sparse, so that their complex behaviour when in close proximity comes into the question only at the collisions which, considering the whole history of a molecule, are relatively infrequent, and then concern only two, or at most three, molecules at a time. In the condensed state any molecule spends its whole life in the immediate neighbourhood of several others, and the prevailing forces, which involve the interaction of several electronic shells, offer a difficult problem which admits of approximate solutions only. From some points of view the crystalline solid is simpler than the liquid state, owing to the regularity of the structure: thus the theory of the specific heats of such solids is on a very sound basis, while the variation of the specific heats of liquids with temperature has so far received no satisfactory treatment. The fundamental difficulty of the solid state, however, is that in general it is not in thermodynamic equilibrium with its surroundings, whereas all ordinary liquids are so. This is particularly true of metals: a metal of a perfectly determined chemical species—that is, either a pure metal or one with definite proportions of other metals dissolved in it—under perfectly determined conditions of temperature and pressure, may have a variety of properties, especially mechanical properties; its behaviour will depend markedly upon its previous history. A mere reference to tempering, or to polish, will be sufficient to indicate what is meant. This variety is emphasized by the division of solid properties, particularly metallic properties, into two classes, structure-insensitive and structure-sensitive. Structure-insensitive properties are those which are comparatively slightly affected by small traces of impurity or by mechanical or thermal treatment—such properties are the specific heat, the overall crystal lattice constants, the density, the coefficient of thermal expansion, and the elastic constants. Structure-sensitive properties are the magnetic permeability and the elastic limit, the tensile strength, ductility, and flow properties—in general, all the mechanical properties of the metal. A striking example is afforded by certain manganese steels of determined composition, which, according to the structure produced by treatment, may be tough, ductile, and non-magnetic, or hard, brittle, and magnetic.

The great difficulties in the study of metals are caused, then, by the fact that very numerous structural differences are possible under like conditions, which means that most of the states in which a metal exists are metastable. In general, a metal in a given state remains indefinitely in that state at room temperature—but there are exceptions, such as the often-cited case of white (ordinary) tin slowly changing into grey tin at temperatures below 18° C, and the many alloys, e.g. various aluminium alloys, which harden if left to themselves at ordinary temperatures or, more rapidly, at a constant, higher temperature. This change, known as precipitation hardening, receives reference later.

If, then, we are going to seek an explanation of the ordinary mechanical properties of metals, we must consider their structure. In the first place, we will take pure metals. It is well known that ordinary metals consist of masses of small crystals, usually referred to as crystal grains, whose existence

can be revealed by polishing[1] the metal and attacking its surface with a suitably chosen reagent which has a preferential action on the crystal boundaries (see figure 1) and frequently on different crystal faces—for individual chemical reagents usually differ in their rate of reaction on different faces of the same crystal. Remarkable cases of selective action were shown by Hausser and Scholz [2] with a sphere turned from a large single crystal of copper, whose preparation was a considerable technical feat. The oxidation that took place in air was confined to the cubic faces of the crystal structure. If the sphere was exposed to nitric acid in which mercury had been dissolved, the rhombic dodecahedron faces were covered with a mercury deposit, the individual faces being separated by bands of bright copper. Examples of the preferential attack on crystal faces of a more ordinary etching reagent are shown by figure 5, where the bright and the dark grains are attributable to this effect.

Another method of revealing the structure of metals by treating the surface in a way that shows selective action is by thermal etching, that is, by heating the metal until the surface layers have been removed by vaporization. This method has, for instance, been used by Chalmers and his collaborators for studying the structure of polycrystalline silver [3], and by Randall and myself for studying the local irregularities of single crystals of cadmium [4]. Chalmers and his collaborators have also studied the attack of gases on heated metals, and have shown that, for instance, oxygen is particularly effective as a revealer of structures. Figure 3 is of a silver surface attacked by oxygen at 900°, showing unstrained twins, while figure 4 is of silver thermally etched in air, showing grain boundaries as well as structure within the grain.

The nature of the intercrystalline boundary has long been a matter of dispute, one school holding that the grains are separated by a region some hundreds of atoms thick, in which the atoms are arranged in a disordered manner—the so-called 'amorphous cement'—and the other school maintaining that between two grains, in each of which a crystal order prevails, is a sheet, a few atoms thick only, the members of which, being under the influence of forces from both lattices, constitute a transitional layer. The latter picture is the one more generally accepted, and very recently Chalmers and his collaborators, applying consideration of free energy to the boundaries, have brought forward strong arguments in favour of it [5].

In a polycrystalline metal we have, then, both crystal grains and crystal boundaries to be considered when we come to seek an explanation of its properties. Further, we have to remember that, with a given metal, the average size of grain may vary within wide limits, according to the method of treatment, and that although the amount of impurity present may be very small—it is never absolutely zero—it may diffuse preferentially to the crystal boundaries, which comprehend so relatively few atoms that the proportion in this region may be appreciable. Again, as we shall see, mechanical deformation may greatly influence the structure and axial orientation of the crystal grains themselves. It should thus be clear that even a spectroscopically pure metal is a very complicated assembly. Its mechanical properties are, however, even more different from the predictions of simple theory than these first considerations of structure would suggest.

Let us turn to the simplest ideal crystal. If we consider two atoms only, they will be in equilibrium under an attractive force tending to bring them together, and a repulsive force which prevents them approaching indefinitely, the repulsive force decreasing with the distance much more rapidly than does the attractive force, with the result that there is equilibrium at E (figure 20), where the two are equal. In the complete lattice, the general picture of prevailing forces is much the same. We should therefore expect that if the lattice were strained, so that the atoms were separated, the resultant force would increase until it reached the maximum, as at M, and that then the metal would break. Until this stage is reached, the ideal lattice should behave elastically, recovering its original size and shape as the stress is removed. We should have, then, large, perfectly elastic deformations, not obeying Hooke's law. Further, we can estimate roughly the theoretical breaking stress of crystals. The only case where the interatomic forces are sufficiently ascertained to enable this to be done from lattice consideration is that of a simple ionic, rock-salt type. Here the result of calculation is that the crystal should fracture under tension at an extension of 14 per cent. and a stress of somewhere about 250 kilo wt/mm². A more general method of estimating the theoretical strength rests upon

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[1] Recently the technique of polishing by electrolysis, in place of mechanical polishing, has been widely used. It has the great advantage of not breaking up the structure of the crystal surface, which suffers considerable local deformation in mechanical polishing [1].

the energy of the fresh surface formed when a rod is broken under tension. The value of the surface energy is given by the surface tension, which in its turn is taken from the surface tension of the liquid, it being assumed that, since the interatomic distances are not much changed on melting, the surface energy of solid and liquid form will be about the same. This method applied to rock-salt gives roughly the same value as that obtained by considering the interatomic forces: applied to metals it gives brittle breaking stresses of the order of 3000 kilo wt/mm². Now the experimental breaking stress of rock-salt is about 0·5 kilo wt/mm², while for metals the elastic limit seldom reaches 50 kilo wt/mm² or the ultimate tensile strength twice this value. The strength of a metal, however it be defined, is even for the toughest steels scarcely a thirtieth of the value to be anticipated from theory for a perfect crystal. If we consider yield under shear we find a similar discrepancy. This very low strength is not the only way in which real metals behave very differently from theory. In general, the region of perfect elasticity is very small: the metal does not fracture in a brittle manner, but there is a large plastic yield, during which the metal toughens ('work-hardening') and, for higher temperatures and stresses, the metal under maintained stress does not retain the dimensions it takes up when first loaded, but slowly flows or 'creeps.' The fracture of metals is a particularly complicated subject, as can be seen from Orowan's recent study [6]. The brittle fracture of certain steels, to which public attention has been directed by the breaking of welded ships, is but one aspect of it, and here it is known that slight variations in the composition of the steel play a major part.

At first, all these anomalies might seem attributable to the fact that the metal consists not of one crystal but of a great number of small crystals separated by the boundaries to which we have referred: these boundaries might reasonably be supposed to be a source of weakness. However, for the past few decades it has been possible to make metal specimens called single-crystal, in which the direction of the crystal axes, as tested by X-rays, is the same throughout. These single crystals can be made in various ways; for instance, by alternately straining and heating the specimen (method of Carpenter and Elam, used particularly for flat specimens); by systematic solidification of the melted metal, enclosed in a vessel, from one end (Tammann, Hausser and Scholz, and others); or by melting the metal locally by a

travelling furnace (Andrade and Roscoe). These are only some examples: many other methods have been used. Single crystals are generally prepared in the form of wires or rods, which a superficial examination might easily take for polycrystalline metal; the fact that the crystal axes are everywhere directionally the same is easily demonstrated, however, by familiar X-ray methods. Figure 2 shows, for example, a Laue back-reflection picture of a gold single crystal, as contrasted with that of a polycrystalline gold specimen. The usual tests can, then, be carried out on specimens of the same size and shape, in which the metal is either polycrystalline or of single-crystal structure.

Strangely enough, the behaviour of metal in single-crystal form diverges from the anticipations of simple theory even more widely than does the behaviour of the ordinary polycrystalline metal. Usually, large plastic deformation begins to take place under stresses much lower than those required with polycrystalline metal: in the one or two cases where brittle fracture takes place (notably with bismuth under particular conditions) the tensile strength is very low, of the order of 1 kilo wt/mm². Deformation leads, in general, to very great work-hardening. What particularly strikes the eye, however, is that single-crystal wires, when extended, show a characteristic structure of bands, such as might be produced by slip, one relative to the other, of a series of parallel planes making a determined angle with the axis of the wire, and that, as the wire stretches, it takes on a flattened form, the normal cross-section becoming elliptical instead of circular. Figure 7 shows a single crystal of cadmium which has been extended by about 40 per cent. This stepped structure is not an effect of impurity. Mercury is probably the metal which can be most effectively purified: stretched single crystals of the purest possible mercury—needless to say, in solid form, which means at low temperature—show the typical banded appearance with great clarity (figure 8). The flattening in extension is illustrated in figure 10, which shows a single crystal of cadmium, extended by about 140 per cent., as seen from two directions at right angles (both normal to the axis of the wire).

Many of the observed phenomena can be explained by supposing that the deformation takes place by glide on particular sets of crystal planes, and in a particular crystal direction. The case of metals with hexagonal crystal structure is particularly simple and may be taken as an example. Here the so-called glide plane, on which slip takes

place, is the hexagonal basal plane, which is unique, in contrast to, say, the octahedral planes in a face-centred cubic crystal, of which there are four equivalent sets. In the glide plane are three equivalent directions in which glide can take place, the digonal axes OC, OD, OE (figure 21): the one which will be operative in any case is that which is nearest to the projection OA of the wire axis on the plane, namely OD in the diagram. Glide will start when the shear stress on the glide plane resolved in the glide direction reaches a certain value s, the critical shear stress for the particular metal. Thus if A is the area of normal cross-section of the wire, F is the applied force in the direction of the wire axis, and χ and λ are the angles made by the glide planes and glide direction respectively with the axis of the wire, the condition for the start of plastic deformation is:

$$\frac{F}{A} \sin \chi . \cos \lambda = s.$$

In cubic crystals of the face-centred type the glide planes are the octahedral planes, such as AED, with three glide directions—MN, PQ, RS—in each, parallel to the triangular edges of the planes (figure 22). This leads to the possibility that a crystal may be so oriented that glide is equally likely to take place on two, or even on three, equivalent planes, as shown in figure 11 for a mercury single crystal and in figure 13 for a gold single crystal.

The critical shear stress s so defined varies from 25 gm wt/mm² to 1000 gm wt/mm² for a range of metals from cadmium to nickel, while the perfect crystal under shear stress should, theoretically, give perfect elasticity up to 50 per cent. shear strain and rupture at 100 kilo wt/mm² or more. Further, it is found experimentally that with single crystals very great work-hardening accompanies the permanent deformation. A particularly striking case is offered by silver, which, according to measurements made in my laboratory, begins to deform at a critical shear stress of 54 gm wt/mm², and breaks, after glide of 95 per cent., at 4500 gm wt/mm². Thus, as mentioned, generally speaking, single crystals show even greater departures from the simple theoretical picture than do polycrystalline metals. There is a further question that confronts us as soon as we look at a stretched single crystal, namely, why the glide occurs in layers, or 'packets' as they are often called, which means that certain planes of a set that in a perfect crystal would be equivalent are particularly favourable for glide. The thickness

of these glide packets at atmospheric temperature is of the order of 1 μ (a thousandth of a millimetre), but it has been shown in my laboratory that the thickness increases very much at high temperatures. Figure 14 shows, for instance, the very coarse glide packets obtained with molybdenum at 1000° C. The glide in the very narrow regions separating the packets is very large: pictures taken with the electron microscope by Heidenreich and Shockley [7] show that with aluminium the laminae (invisible under the ordinary microscope) that make up the region of intense slip are about 200 A (roughly 70 atom diameters) thick, and may be displaced relatively to one another by 2000 A.

The abnormal weakness and the possibility of very large permanent deformations which, in general, characterize metal single crystals can be explained only by postulating flaws in the crystal structure, deviations from the perfect crystal lattice. Such deviations are now generally called 'dislocations'; to appreciate the fitness of the term it must be remembered that it signifies merely the movement of something from its right place. The simplest dislocation in a lattice, of a kind invoked by G. I. Taylor in his theoretical work on metal strength, can be illustrated by a two-dimensional case, represented in figure 23. The top rows symbolically represent a nearly perfect lattice. In the seventh row from the top there is a local expansion of the atomic spacing, resulting in a misfit, or dislocation, centred on the spot marked by the arrow, with a corresponding irregularity of the surface of the crystal, represented by the atoms to the extreme left. Owing to the modification of the atomic forces caused by the abnormal positions, the marked atom is less firmly held than is the case in the normal lattice, and it is possible to move it sideways by a comparatively small horizontal shear, bringing the neighbouring atoms with it, so that the next atom becomes the centre of the dislocation, moves in its turn under the small shearing stress, and so on, the dislocation passing along a horizontal line.

To illustrate the passage of a dislocation, which is a fundamental feature of all modern theories of the deformation and hardening of metal crystals, I made some time ago a dynamic model, illustrated in figure 6 [8]. The white disks in the photograph are the ends of wooden cylinders, about three inches in diameter, the lower row being fixed and the upper row resting on them, each one in a (gravitational) potential hollow. The cylinders of the upper row are also connected by a black
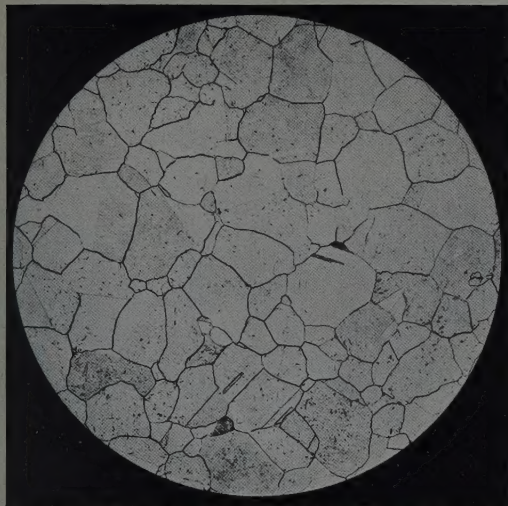
FIGURE I – *Polycrystalline lead with grain boundary etch.* (× 9)
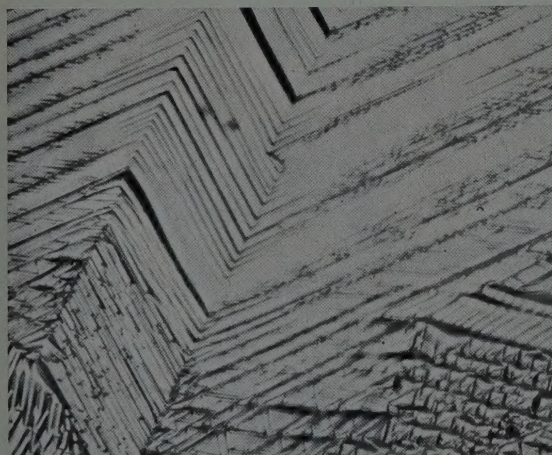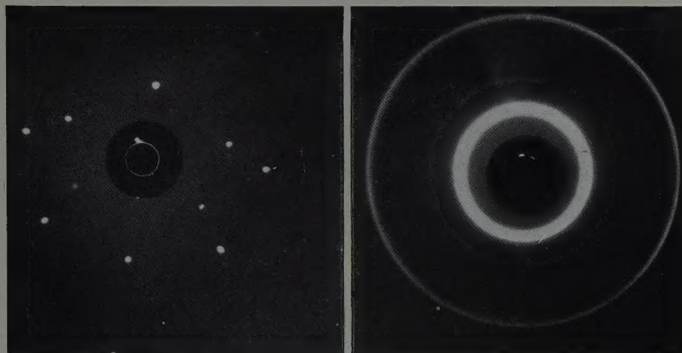(*By courtesy of the British Non-Ferrous Metals Research Association.*)

(a)   (b)

FIGURE 2 – *Back-reflection X-ray photograph of a gold wire:* (a) *Single crystal,* (b) *polycrystalline state.*
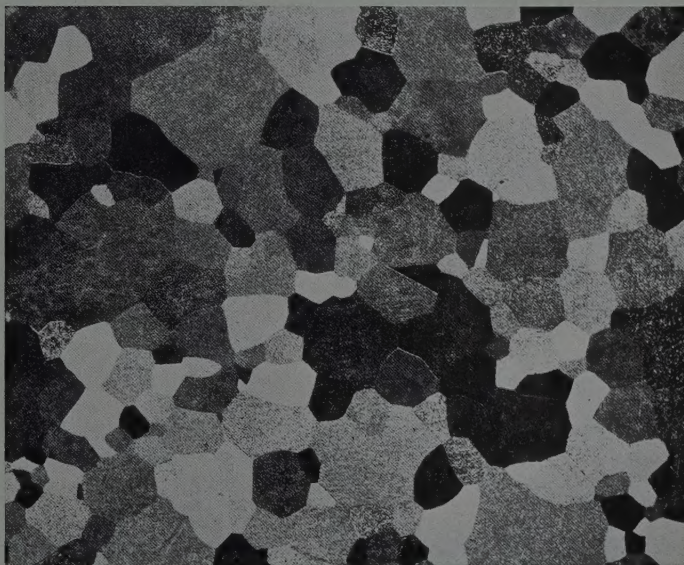(*Photograph by Dr C. Henderson, Carey Foster Laboratory.*)

FIGURE 3 – *Silver thermally etched in oxygen.* (× 1500)
(*Photograph by Mr R. King.*)

FIGURE 4 – *Silver thermally etched in air.* (× 540)
(*Photograph by Mr L. Walden, Carey Foster Laboratory.*)

FIGURE 5 – *Aluminium containing* 0·5 *per cent. silver: same metal, two different grain sizes.* (× 10)

FIGURE 6 – *Model to illustrate propagation of a line dislocation.*
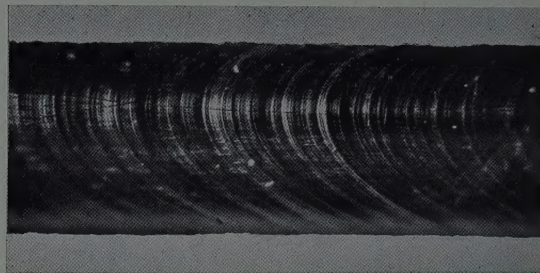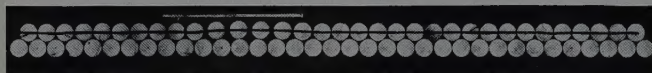
FIGURE 7 – *Cadmium single crystal, extended by 40 per cent.* (× 30)   (*Photograph by Mr L. Walden, Carey Foster Laboratory.*)
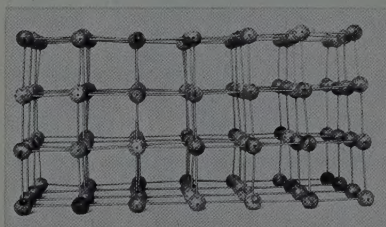
(a)
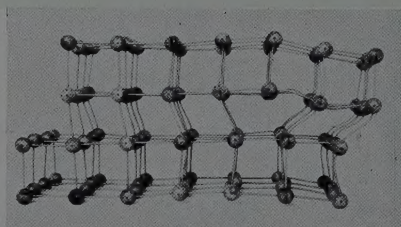
(d)
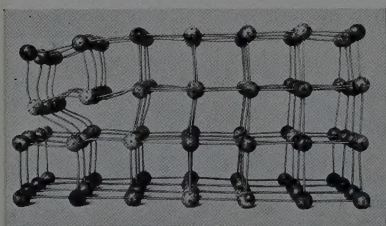
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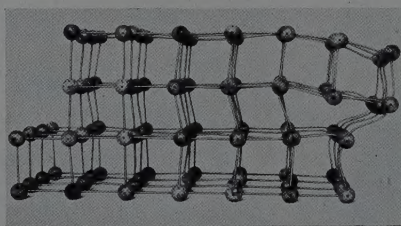
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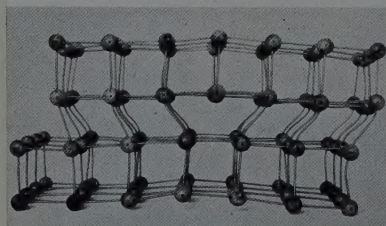
(c)
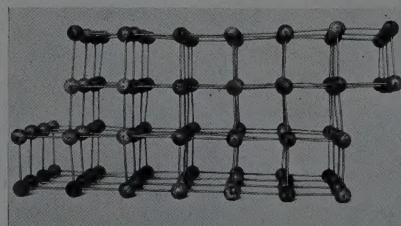
(f)

FIGURE 9 – *Three-dimensional model of line dislocation.*
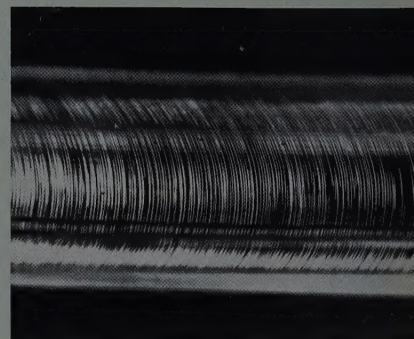(*By courtesy of Dr B. A. Bilby and The Institute of Metals.*)

FIGURE 8 – *Stretched single crystal of mercury.* (× 16)
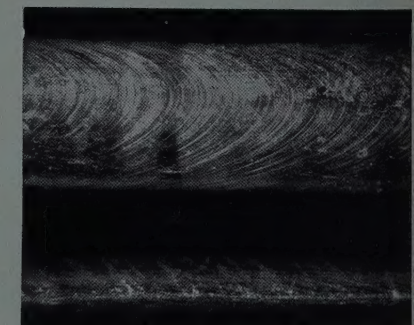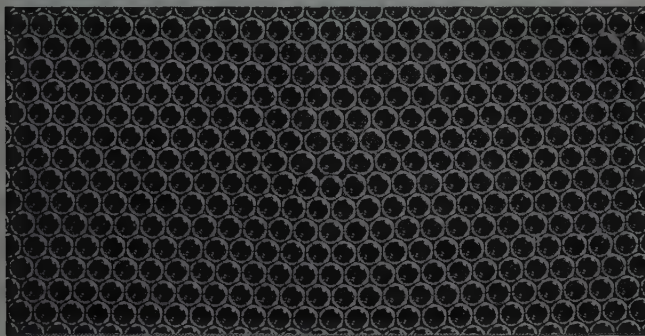(*Photograph by Dr K. M. Greenland, Carey Foster Laboratory.*)

FIGURE 10 – *Cadmium single crystal, extended by 140 per cent., as seen flat on and edge on.* (× 22) (*Photograph by Mr L. Walden, Carey Foster Laboratory.*)

FIGURE 11 – (a) *Double glide*, (b) *triple glide, in mercury single crystal.* (× 16)
(Photograph by Dr K. M. Greenland, Carey Foster Laboratory.)

(a)

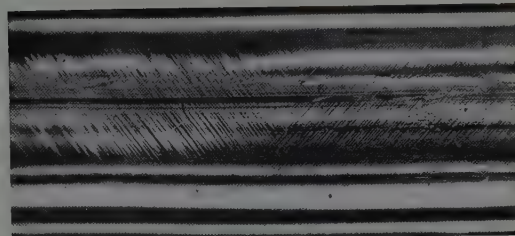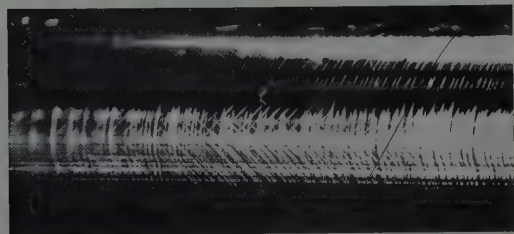(b)

(a)

(b)

(c)

FIGURE 13 – *Triple glide in gold single crystal.* (× 1800)
(Photograph by Dr C. Henderson, Carey Foster Laboratory.)

FIGURE 12 – *Bubble model:* (a) *A grain boundary,* (b) *a dislocation, in middle of picture,* (c) *effect of a larger foreign atom.*
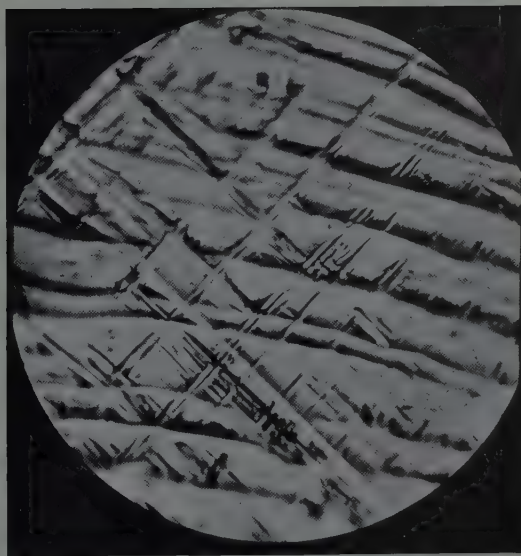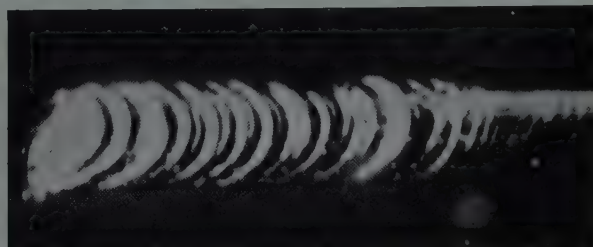*(By courtesy of Sir Lawrence Bragg, Dr J. F. Nye, and The Royal Society.)*

FIGURE 14 – *Coarse glide packets on molybdenum single crystal at 1000° C.* (× 65)
(Photograph by Dr L. C. Tsien and Dr Y. S. Chow, Carey Foster Laboratory.)
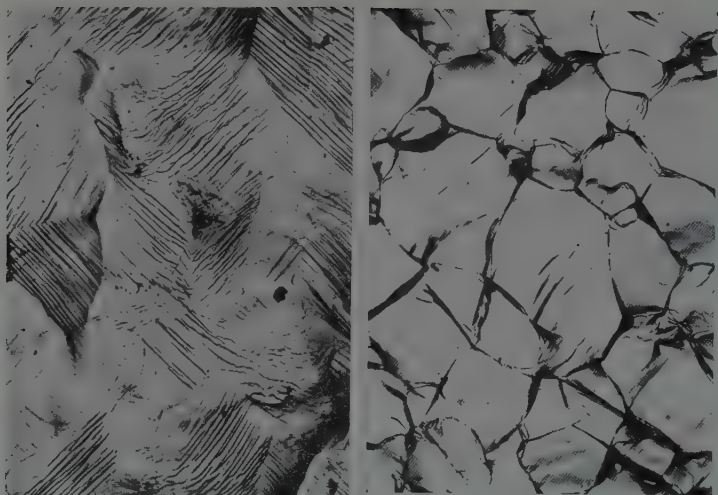
FIGURE 15 – *Aluminium (left) after 9 per cent. rapid strain at 200° C, (right) after 8 per cent. rapid strain at 500° C. (× 100)*

(By courtesy of Dr W. A. Wood and Mr W. A. Rachinger, and the Institute of Metals.)

(a)

(b)

FIGURE 16 – *Laue back-reflection photographs of silver single crystal, (a) unstretched, (b) highly stretched.*

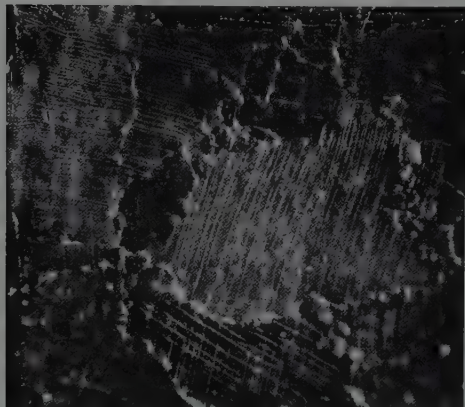(Photograph by Dr C. Henderson, Carey Foster Laboratory.)

FIGURE 17 – *Slip lines in grains of polycrystalline lead.* (× 60) (Photograph by Mr K. H. Jolliffe, Carey Foster Laboratory.)
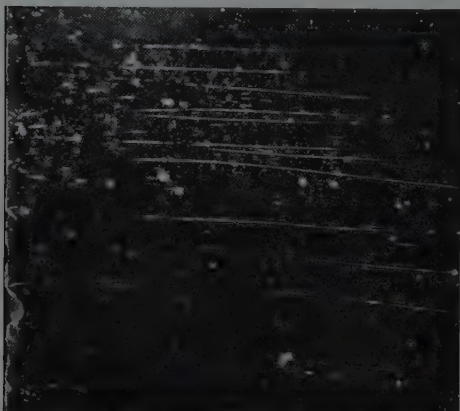

FIGURE 18 – *Griffith cracks on Pyrex glass surface revealed by attack of sodium vapour.* (× 14)

(Photograph by Professor E. N. da C. Andrade and Dr L. C. Tsien.)
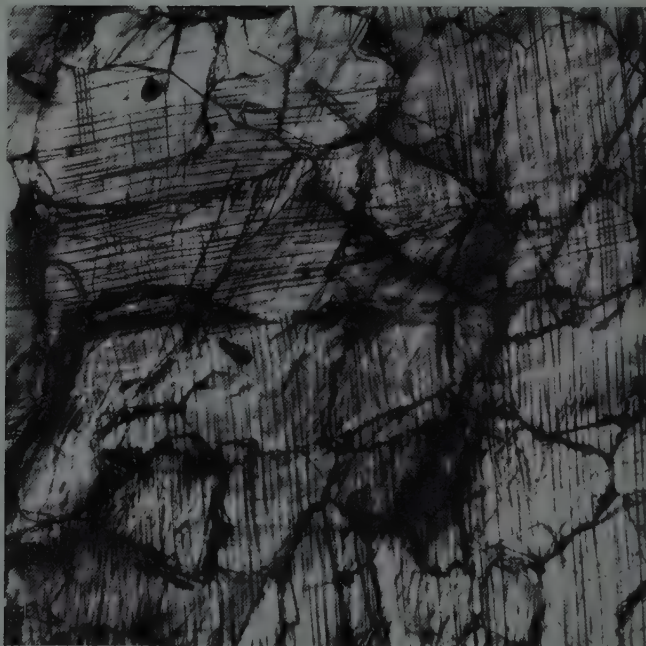

FIGURE 19 – *Slip in recrystallized lead, showing old boundaries.*

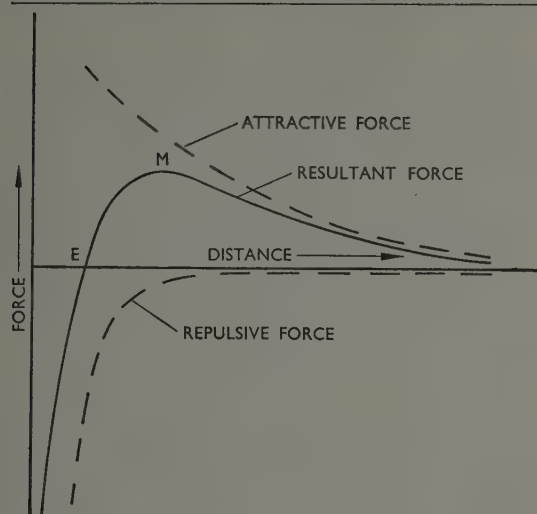(Photograph by Mr K. H. Jolliffe, Carey Foster Laboratory.)

FIGURE 20 – *Diagram to illustrate interatomic forces.*

elastic band, attached to the centre of each cylinder, to represent horizontal interatomic forces. When the upper row is compactly spaced, as in the topmost picture, it is impossible by ordinary pushing to make it travel by one spacing over the lower row: this would involve making all the cylinders mount simultaneously over the crests of the hollows in which they lie. Let us now make a dislocation, as shown by the widened spacing under the white line in the second picture from the top. The middle cylinder of the dislocation is not in a hollow at all, and it is very easy to move it one to the left, which makes the centre of the dislocation move one to the right. The third and fourth pictures show the travel of the dislocation, produced by passing the hand over the cylinders. In the lowest photograph, the dislocation has travelled to the end and the whole row is displaced by one spacing.

Dr Bilby [9] has made some excellent three-dimensional models to illustrate different types of dislocation.[1] The series representing the travel of the simple line dislocation which we have been

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[1] The dislocation represented by the two-dimensional case is, of course, the same in a three-dimensional crystal, in every plane parallel to the paper, so that, as it passes, the whole upper half of the crystal is displaced with reference to the lower half of the crystal. It is called a line dislocation. If, in the three-dimensional case, only a small length of the crystal, considered at right angles to the paper, as distinct from the whole width, is shifted with reference to the crystal below, a more complicated form known as a screw dislocation may arise (see e.g. A. H. Cottrell in *Progress in Metal Physics*, 1949). Curved line dislocations have also been considered by the theorists.

considering is given in figure 9, where *a* is the perfect lattice; *b* is the lattice with a line dislocation near the left-hand side; *c*, *d*, and *e* are various stages of the travel; and *f* is the final state caused by the passage of the dislocation.

Sir Lawrence Bragg and Dr Nye [10] have perfected a spectacular way of illustrating many properties of metal crystals. Each atom is represented by a single bubble in 'rafts' of very uniform small bubbles produced by a special device. In figure 12 are examples of the bubble model, (*a*) showing a grain boundary, (*b*) a dislocation, and (*c*) the disturbance produced in the lattice by a large (foreign) atom.

This conception of glide by travelling dislocations explains the softness of metal single crystals, why polycrystals are harder, and why, in general, a metal with very fine grains deforms less readily than one with coarser grains. For the propagation of a dislocation a fairly regular structure is necessary, the centre of disturbance being handed on
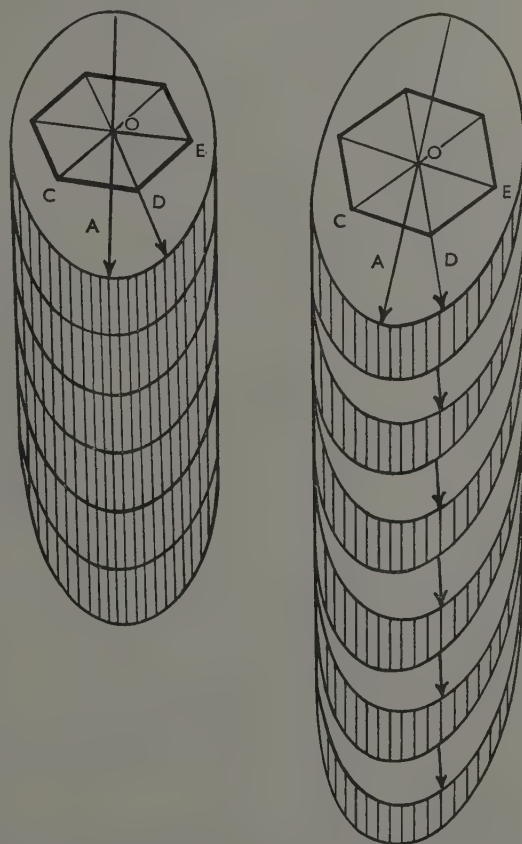

FIGURE 21 – *Diagram to illustrate extension of single-crystal wire of metal of hexagonal structure.*

unchanged from one spot to the next. The break in the regular crystal structure at the grain boundary holds up the propagation of the dislocation. The slip lines within the grains of a polycrystalline metal, and their termination at the boundary, are well shown in figure 17. Any lack of homogeneity in the structure may also harden the metal by arresting the run of the dislocation. Thus the hardening of single crystals by impurities can be explained as due to local strains produced by stranger atoms, as illustrated in figure 12 (c), which check the run of the dislocations. The mechanical effect of precipitation from a supersaturated solid solution of particles which do not fit into the lattice—the so-called precipitation-hardening—has been attributed to these local strains, and Mott and Nabarro [11] have worked out a mathematical theory of the phenomenon.

One great problem of the single-crystal state is the marked hardening which always takes place with permanent strain. The critical shear stress increases as the crystal is deformed by glide, at temperatures that are not too high—and, as a rough rule, it is the ratio of the prevailing temperature to the temperature of melting that is effective when we speak of high or low temperatures. There is strong evidence that this hardening is connected with local break-up of the single-crystal structure. It is found that with strained crystals we no longer get distinct Laue spots, such as are shown in figures 2a and 16a, but that each spot becomes smeared out into a line. This extension of spots, due to the existence in the crystal of
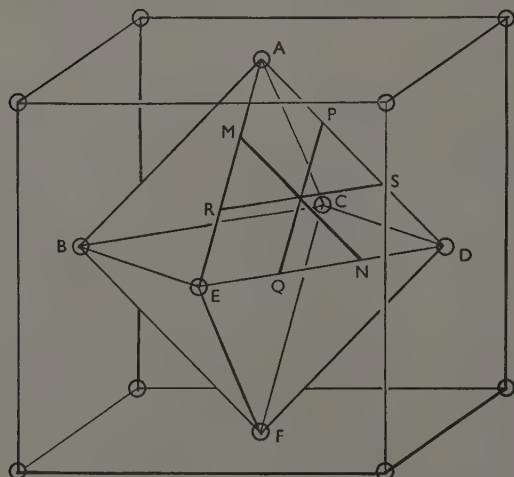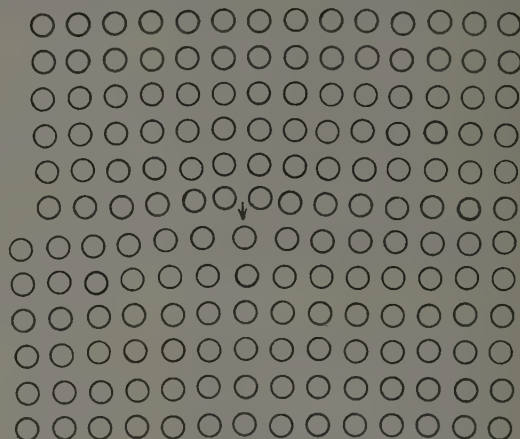

FIGURE 23 – *Diagrammatic representation of line dislocation.*

planes rotated through small angles from the normal, is called asterism: an example is given in figure 16b. It has been shown in my laboratory that the hardening is proportional to the spread of angle indicated by the asterism. The hardening of single crystals under strain is, then, due to the fact that they lose something of their single-crystal structure, with a consequent creation of obstacles to the run of dislocations.

The effect described by Rehbinder of a surface-active agent (such as oleic acid) in promoting flow, which he attributed to penetration of the liquid into minute cracks, seems to be due to the disintegration of thin films of surface oxide, which inhibit slip. Randall and I have found that the flow of ordinary single crystals of cadmium is enhanced by the contact with the surface of electrolytes containing cadmium ions, but that if the surface of the wire is cleaned by heating it *in vacuo* until considerable vaporization has taken place, there is no such effect [12]. Heating a cadmium single-crystal wire in air so as to produce light surface oxidation puts up the critical shear stress. To be brief, a range of observations indicates that it is possible that most, if not all, of the dislocations start at the surface, and that any kind of oxide contamination tends to hinder their effectiveness.

An effect which must be taken into account in many problems of metal strength was brought into prominence by A. A. Griffith. The mathematical theory of elasticity shows that in a solid the stress at the end of any crack or fissure is

FIGURE 22 – *Glide elements of metal of face-centred structure.*

much above the average. In particular, for a crack of elliptic cross-section, of major and minor

axes *a* and *b* respectively, the maximum stress, in the neighbourhood of the greatest curvature, is $\sigma (1 + 2a/b)$, where σ is the stress a long way off. Hence, in particular, anything in the nature of a surface crack may lead to a very high local stress, provided—and this is often forgotten—that the material may be treated as a perfect elastic solid. Local plastic yielding will, of course, completely invalidate the calculation. The existence of microscopically invisible surface cracks has not been proved in metals, but Andrade and Tsien [13] have shown that they can be revealed in glass by the attack of sodium vapour and by other means (see figure 18). Such microcracks are referred to as 'stress-raisers'; if of atomic narrowness they may lead to very large local stresses. Larger, microscopically visible, microcracks play a great part in fatigue failure of industrial metals. If Griffith cracks exist in the surface of single-metal crystals and are the origin of dislocations, the large effect of such things as the oxide coatings can be easily understood, since they may effectively heal such narrow fissures. The distribution of Griffith cracks of varying severity in the surface may help to account for the existence of the glide packets, to which attention has already been directed, rather than uniform glide on all crystallographically equivalent planes. This is a complicated question, but there is much evidence for faults spaced at something of the order of 1μ in metal single crystals. The striations in the grains of the silver crystals of figures 3 and 4, revealed by thermal evaporation, have, for instance, approximately this spacing, as have the separations of the slip bands in most metals at temperatures not too high, and also certain markings revealed by the thermal etching of single crystals of cadmium [4]. Straumanis has shown that cadmium crystals formed from vapour (and in other ways) are laid down in steps of thickness of the order of 1μ. The stress-strain relationship for single crystals, even those with only one system of glide planes, is a complicated matter, to explain which the interaction of local stress concentrations caused by lattice irregularities has been invoked. In short, the mechanical behaviour of single crystals of metals, even of spectroscopic purity, can be explained only by a system of faults in the crystal structure.

When the behaviour of the single crystal under comparatively simple stress systems is so complicated, it is not surprising that the problems of the practical metallurgist, dealing with polycrystalline systems of many components under such involved stresses as those produced by, say, rolling, are extremely difficult to treat theoretically. No attempt at a survey can be made here, but something may be said about a problem that has recently assumed great engineering importance, namely the flow of metals under high stresses and temperatures. The gas turbine in all its forms is dependent upon steels that, at the temperatures in question, must not systematically creep under the stresses produced by the high speeds of revolution. Even in the practical utilization of nuclear energy the creep of metals is involved: thus, treating of the power-level of an atomic pile, Sir John Cockcroft says: 'The decreasing creep-strength of aluminium with increasing temperature would probably limit surface temperatures to about 350° C.' Hence the laws of creep have considerable practical as well as theoretical significance.

Most experiments on creep have been carried out with cylindrical rods under tension. If the stretching force is applied by a constant load, then, since the cross-sectional area diminishes as the rod extends, the stress increases with time, which complicates matters. Various devices have been contrived for diminishing the load automatically in such a way as to maintain the stress at a constant value [14]. Under these conditions, the curves shown for lead (figure 24) are typical of a range of pure metals. At a low temperature (− 180° C) there is a large immediate extension, followed by an increase of length at a very slow rate, which decreases and ultimately becomes zero. At a somewhat higher temperature (− 78° C) the creep is more marked but ultimately becomes vanishingly small. At room temperature, the rate of creep is much larger and the rate approaches a finite constant, while at high temperature (160° C) the main part of the creep curve exhibits a constant rate. The curves shown in figure 24 are for short times of flow only, but the laws now to be given have been verified over much longer durations. While the curves shown are for lead, they are representative for all the pure metals systematically tested under conditions in which recrystallization does not take place: thus the creep behaviour of iron at 450° C resembles that of lead at 16°, and the creep behaviour of iron at 16° resembles that of lead at − 180° C.

It is found that the behaviour can be represented by the equation:

$$l = l_0(1 + \beta t^{\frac{1}{3}})e^{\kappa t},$$

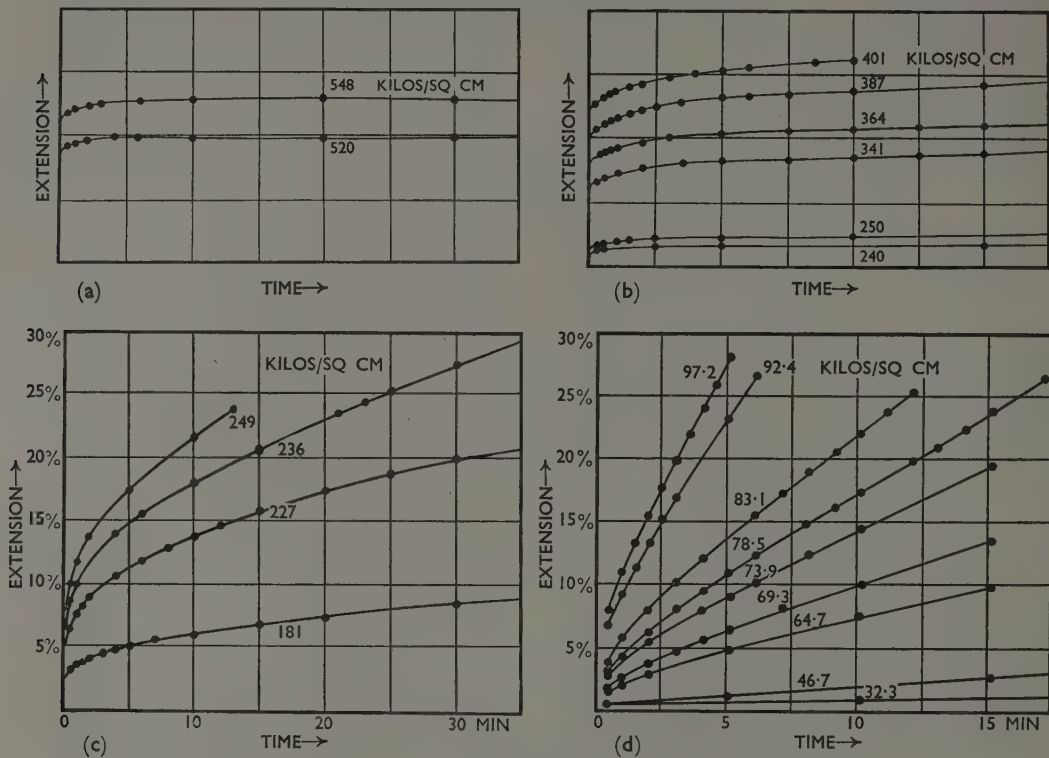where l_0, β, and κ are constants. The exponential term represents flow at a constant rate per unit

FIGURE 24 – *Creep in polycrystalline lead at various temperatures and stresses:*

(a) — 182° C, no permanent flow.
(b) — 78° C, no permanent flow.
(c) 17° C, transient flow and permanent flow.
(d) 160° C, permanent flow predominant.

length, and is caused by the fact that the length flowing increases during the experiment: thus if $\beta = 0$,

$$\frac{1}{l}\frac{dl}{dt} = \kappa.$$

The importance of this analysis is that it divides the flow into two parts: one part proportional to $t^{\frac{1}{2}}$, that is, diminishing in rate very rapidly, and the other proportional to t, that is, proceeding at constant rate. The part measured by β is called the β flow or transient flow; that represented by κ is the quasi-viscous or permanent flow. At low temperatures $\kappa = 0$. In this connection 'low temperature' means, as has been already pointed out, temperature low compared to the melting point.

It is now generally accepted that the transient flow is connected with slip within the grains and the permanent flow with relative movement of grains [15]. Thus Hanson and Wheeler, working with aluminium, found that, at low temperature and rapid deformation (favourable to transient flow), well-defined slip lines terminating at the boundary, such as are exemplified in figure 17, appeared within the grains, while at high temperature and slow deformation (favourable to permanent flow) the grain boundaries became much emphasized, and eventually intercrystalline cracks appeared. This is well shown by some photographs, also of aluminium, due to Wood and Rachinger [16]. Figure 15a is after 9 per cent. rapid strain at 200° C, which may be reckoned a low temperature for aluminium: the slip lines in the grains are well seen. Figure 15b is after 8 per cent. rapid strain at 500°, which is a high temperature: the boundaries are broad and dark, but there are few slip lines. It was earlier shown [14] that the transient flow was connected with a rotation of the axes in the grain, which is in accordance with the slip on crystal planes. The $t^{\frac{1}{2}}$ law has apparently great generality, but no fully satisfactory theory of it is yet established. The flow of metals

has recently been studied in my laboratory under pure shear, and in these conditions the $t^{\frac{1}{3}}$ law has been fully confirmed. The permanent flow does not take place with the particular system of stressing used, a fact that accords well with the view that attributes it to intergranular movement.

In many cases, the creep in metals is complicated by the fact that recrystallization takes place during the flow, especially with the steels used in high-temperature engineering. It also takes place with very pure lead during flow. In the process of recrystallization, certain small undistorted grains tend to enlarge their domain at the expense of others, with consequent movement of boundaries. Figure 19 is a striking photograph taken in the course of work which we have been carrying out under pure shear. The crystal boundaries so plainly marked are the original boundaries, brought into prominence by etching, but extensive recrystallization has taken place, as shown by the slip lines, running in some cases right across the picture. These indicate that one crystal domain now covers most of the photograph, the apparent grain boundaries being only the old surface markings—old shallow ditches across which the plough has been driven now that the original small fields have been incorporated in one farm. During recrystallization, flow is enhanced: the main features of flow under these conditions are now satisfactorily explained.

Needless to say, this brief account does not even mention many important branches of the subject. The study of the basic mechanical properties of metals is one that has sprung into prominence in the last twenty years or so, and at the present time it is being actively pursued in Britain in the universities of Cambridge, Bristol, Birmingham, and London, as well as in many government and industrial laboratories. In 1934, the date of the international conference on the solid state of matter (London), there was hardly a book devoted to the physical aspects of metal strength. In 1935 appeared Schmid and Boas's *Kristallplastizität*: since then there have appeared in England, Germany, France, and the United States a number of significant books dealing with what is often called metal physics, regardless of the fact that this term should include the thermal, optical, and electrical properties as well as the mechanical properties. After long neglect, the interest and importance of seeking some explanation of the most obvious properties of the metallic state, many of which have been known to craftsmen for generations, are becoming realized. The atomic nucleus, of course, remains supreme, but the way in which metallic atoms hold together and modify their assemblies under the rough treatment to which they are subjected has its attraction as a subject of study.

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Land erosion

SIR CYRIL FOX

The process of erosion is of great importance in the geological history of the world, for it is one of the main factors bringing about the immense changes which slowly alter the whole configuration of the earth's crust. Recently, man's activities have sometimes resulted in local erosion so rapid as to turn great tracts of fertile land into deserts. Knowledge of the mechanism of erosion is therefore of great practical, no less than of theoretical, value.

INTRODUCTION

The word erosion has been used for the last 120 years by geologists to denote those natural processes which wear or eat away the substance of the earth's crust. The term covers a wide range of physical and chemical actions—removal of soluble matter, chemical changes, disintegration by frost or rapid changes of temperature, attrition by dust-charged winds, scouring by silt-laden currents, alternate impact and suction by storm waves, landslides, and so on. During the last forty years the question has arisen whether the term erosion should not cover agents acting more quickly, such as volcanic explosions, and man's activities in the removal of minerals. All aspects of one of the most important studies of the earth's crust are a fundamental concern of the field geologist.

GORGES AND CANYONS

It is often difficult to explain why a river has cut a gorge when, from existing topography, it might have made an easy detour. The rate of erosion is influenced by the nature and structure of the rocks, and by any regional uplift or sinking which may be in progress to increase or decrease the gradient of the river. The most spectacular and greatest example is the Grand Canyon of the Colorado River in Arizona, estimated at 300 miles long, with an average depth of 0·65 miles and width of 10 miles, figures which provide a measure of the volume of rock removed by stream erosion. The strata are, for the greater part, relatively soft Palaeozoic sandstones, shales, and limestones, which slope gently to the south-west, with some Pre-Cambrian (Algonkian) and Archaean (gneisses) in the bottom (floor and sides). The Rocky Mountain uplift has kept the tilt to the south-west and thus maintained the gradient of the Colorado River in that direction. However, it is clear that the silt-laden waters of the river have been the chief cutting agents in excavating the Grand Canyon. At present, the silt carried by the Colorado River into Lake Mead is estimated at 0·01 cubic miles annually. If this can be taken as an average also for the past, the gorge is approximately 200,000 years old (the figure is so large that one extravagant guess is as good as another). In contrast to this, the Niagara River, as it races over the limestone (Silurian) to the American and Canadian Falls from Lake Erie, is clear and siltless. With the drop of 165 feet into the swirling waters below, and the action of fallen blocks of stone, a great scour proceeds in the Medina shales, which leads to the undermining of the overlying strata and the regression of the falls. The Palaeozoic strata dip gently south-west, and the gorge below the falls is now nearly 7 miles long. The advance of the gorge from Lake Ontario has been computed at about 2 feet a year, so that the falls may be roughly 20,000 years old. It should be mentioned, however, that an uplift to the north-east has been in progress in this region since the Canadian (Pleistocene) ice sheet slowly retreated and unloaded its weight from the earth's crust over Ontario. This movement would tend to reduce the gradient of the Niagara River, but it is doubtful if it has seriously affected the rate of regression of the falls.

COAST EROSION

Many cyclones from the Bay of Bengal, travelling towards the Ganges Delta just ahead of a high tide, have forced a storm wave 40 feet high into the estuaries and over the low-lying country. The cyclone of 1864 left a vessel of 2185 tons high and dry on Shalimar Point, near Calcutta. However, it is the 'backwash' or retreating waters which have destroyed crops and swept away thousands of people and cattle. The Backerganj cyclone of 1890 was followed by famine and disease. The retiring wave appears to converge towards the position of the 'swatch of no ground,'

FIGURE 1 – *A Baluch defile near Mach, showing the canyon cut by floor*
[wa]ters assisted by a big boulder which acted as a borer. (Photograph by
[Cy]ril S. Fox.)

FIGURE 2 – *Typical V-notch produced by stream erosion on a slope. The*
water has carried out a deltaic fan of débris. (Photograph by J. B. Auden.)

FIGURE 3 – *Stream erosion, showing the effect of scouring over jointed sandstone by a small flood*
from a weir. The water has scoured out all the soil in the fissures of the sloping sandstone. (Photo-
graph by W. D. West.)

FIGURE 4 – *A Himalayan river, the Sutlej at Chabar, north of Simla, showing the river re-excavating two older river terraces.* (*Photograph by W. D. West.*)

FIGURE 5 – *The Chappar Rift, below Mud Gorge, on the railway to Quetta. The small stream leaving the gorge has cut through an arch of Eocene (Dunghan) limestone in a typical V-notch.* (*Photograph by Cyril S. Fox.*)

off the delta, and it is believed that the deep water there is due to scouring by such flood waters. The erosion of tidal currents and storm waves has long been demonstrated near Hilderthorpe in Bridlington Bay on the Yorkshire coast, England, but the severity of the action appears to be due to lack of sufficient hard material. The glacial boulder clays exposed contain too few boulders to furnish a protective or storm beach, such as the famous Chesil Bank on the Dorset coast. This shingle bank extends as a natural feature for 18 miles, from near Bridport along the coast to Abbotsbury, and so to Portland Island, where the quartzite pebbles disappear into the sea, having been moved along 25 miles by the surge and scour of the tides and waves from Budleigh Salterton, under Lyme Bay, to near West Bay, and then along the Chesil Bank to Portland Island. At Budleigh Salterton the pebbles fall from the cliff on to the beach, which is a protective apron to the cliffs. The material in the pebble beds (Triassic) was derived from a Palaeozoic (Ordovician) sandstone, so that the original pebbles were produced more than 150 million years ago—and are being utilized again—from material eroded from older rocks 400 million years ago.

LANDSLIPS AND MUDSLIDES

In certain arid regions where a wide valley is filled with an alluvial deposit of mud and gravel, a sudden heavy fall of rain may convert the material into a liquid which moves like a stream of lava and flows for considerable distances. The Mud Gorge in Baluchistan, named after the trouble encountered by early railway engineers, is famous for pyritiferous shales (Eocene) which, after weathering, become of the consistency of liquid mud. These are extreme cases of soil and subsoil on hillsides becoming waterlogged, and losing the cohesion which enabled the mass to stand at a high angle of repose. In the case of the Gohna Landslip in Garhwal (Himalayas), the hillside was composed of crumpled dolomitic limestone and pyritiferous shales, etc., tilted at an angle of 45° towards the Birahi Ganga valley. After a period of heavy rain a plane developed on which the overlying mass slipped down 3000 feet; it even rose some distance up the farther slope. It filled the valley for a width of 2 miles and to a height of 850 feet (to the saddle) with about 5000 million tons (0·5 cubic miles) of rock débris; a snowy dust settled on everything for miles around. It took a year for the lake to fill, but when the water overflowed at the saddle 12×10^9 cubic

feet of water were discharged, and the 'dam' was cut down 400 feet with extreme rapidity. The flood water rushed down the valley at 20 miles an hour, and at a depth of from 100 to 170 feet far downstream. Perhaps the largest known landslip is that called the Saidmarreh of Luristan, Persia, which occurred in prehistoric times. The scar shows for 9 miles, indicating a mass 1500 feet high and 2·5 miles wide. The material buried the confluence of the Saidmarreh and Kashgan rivers to a depth of 1000 feet. The gorge breached by the impounded waters is still 400 feet deep, and the débris can be traced over 64 square miles. The mass was estimated at over 4 cubic miles.

VOLCANIC EXPLOSIONS

The volcanic dust from the violent eruption of Vesuvius in A.D. 79 buried the Roman cities of Pompeii, Stabiae, and Herculaneum so completely that their sites were lost for centuries. More recent, and far more violent, was the explosion of 1883 which blew the island of Krakatoa out of the sea. The island was estimated at 3 miles by 5, and rose to 2500 feet above sea level, while the cavity after the explosion was 1000 feet below sea level. The volume of lava, pumice, and dust blown up is estimated at over 5 cubic miles. The volcanic dust attained a height of 90,000 feet, the sea waves on the adjacent coast repeatedly surged to 80 and 100 feet, the dust caused darkness within a radius of 25 miles, and two weeks after the explosion the pumice floating in Lampong Bay, 50 miles to the north, was 14 feet thick. A similar event occurred in 1912, in Alaska, when Mount Katmai exploded and left a crater 3 miles across and 3700 feet deep. Kodiak Island, 100 miles away, received a coat of dust more than a foot deep. The Valley of Ten Thousand Smokes, which came into existence at that time, is now included in the Katmai National Memorial. It is estimated that the material blown out as pumice and dust must be regarded as about 5 cubic miles.

EROSION BY RIVERS

The work of rain and rivers is usually done quietly and gradually, but it requires heavy rain and floods to sweep away the decomposed rock or detrital material. Figure 1 shows a Baluch defile, near Mach, which was rapidly cut by the tremendous floods which follow any heavy rain in this arid region. The 'secret of the chasm' is the large boulder seen in the floor. It is lifted and rotated by the eddy that develops at this point, and becomes a veritable boring machine which

drills into the bed and deepens the defile during each period of flood. Another example of stream-bed movement was discovered in the Black Canyon, when the Hoover (Boulder) Dam was built. Under 40 feet of sand a piece of sawn timber was found resting on the main rock floor, and an inner deep canyon was discovered extending 70 feet below. The scoured condition of the rock walls of the inner canyon, together with the evidence of the timber, showed that the entire mass of sand which covered the floor of the Black Canyon must have been in turbulent movement through the gorge whenever the Colorado River came through in high flood. Since the various dams have been built and the reservoirs above each have become silt traps—Lake Mead above the Hoover Dam and Lake Havashu above the Parker Dam, etc.—it is noticeable that the river is now re-excavating silt it had previously deposited as bed load. This erosion is taking place below the dams, as the river does not now replenish the deposits which the floods bore downstream.

The erosion from a large drainage area, the Mississippi (1.25×10^6 square miles), with its eastern humid region and arid western plains, amounts annually to 80 tons of dissolved matter, 288 tons of suspended silt, and 32 tons of bed load from each square mile; it is carried into the Gulf of Mexico. In the case of the Nile, which draws its floods and silt almost entirely from the erosion of the Abyssinian highlands during the rains, the annual totals are 57×10^6 tons of fine silt and 20×10^6 tons of soluble matter from half the total catchment of 1.5×10^6 square miles, at Aswan. The Nile floor is under erosion from Khartoum to Aswan, and re-excavation of older alluvium is in progress between Aswan and Cairo. This river-bed erosion is thought to be due to rejuvenation by a steepening of the river gradient, as a result of the weight of the deltaic alluvium on the one hand, and unloading (by erosion) in the region to the south-east and south of Aswan on the other. If an assumption of 300 tons of material removed per square mile per year is accepted for the land surface of the earth (57.5×10^6 square miles)—allowing 210 tons for suspended matter, 60 tons for dissolved material, and 30 tons for bed load—the annual erosion will amount to 2.177 cubic miles (1.531, 0.431, and 0.215 cubic miles respectively for the silt, solubles, and bed load). The amount of land above sea level is estimated at an average elevation of 2500 feet, say 0.5 mile, therefore the volume will be 28.75×10^6 cubic miles.

With erosion at the rate of 2.177 cubic miles annually the entire land area of the earth would be reduced to a base level in less than 14×10^6 years.

CONCLUDING REMARKS

As considerable areas of the land surface are not under active erosion—deltas, deserts, lakes and regions of inland drainage, and the polar regions under thick ice sheets—it is certain that the rate of erosion assumed in the previous paragraph is too high; but at even a quarter of the rate of 2.177 cubic miles, the continental regions would, theoretically, be worn down to sea level within 60×10^6 years (since the beginning of the Eocene period). Although erosion (and sedimentation) began on the earth's surface in a Pre-Cambrian era perhaps 15×10^8 years ago, it is safe to say that 5×10^8 years have elapsed since the earliest fossiliferous strata were laid down in a Cambrian sea covering part of Wales. The total thickness of strata laid down, in one part of the world or another, during the successive geological eras—Lower and Upper Palaeozoic, Mesozoic, and Kainozoic—may, if put as in a single vertical column, amount to 60 miles (316,800 feet). They were not, however, deposited to this amount, or to even a quarter that thickness, in any one region, nor were they all deposited in the sea. If they represented the volume of the present land mass, in the form of silt (1.746 cubic miles annually), a pile of that height would cover less than 480,000 square miles of the earth's surface. We must recognize then that, even at the slowest rate of erosion, the materials of the earth's land mass could have been eroded over and over again at least eight or nine times. There is thus evidence, irrespective of the data obtained by seismologists, that erosion and sedimentation upset the balance of loading on the earth's shell, and that, in consequence, the outer crust bends and buckles. Indeed, these adjustments take place rapidly, and the crustal movements must, in the course of time, lead to folding and faulting and such crumpling and kneading that sedimentary rocks may be forced deep into the crust in some places, and elevated in other cases. Thus we find Permian strata forming the mass of Everest, but may not recognize the dust of Krakatoa as the fused débris of perhaps an Eocene clay, and some granites may be the recrystallized form of sediments which were forced down to the base of the Sial layer at the Mohorovičic discontinuity.

Ecology of ciliate infusoria

E. FAURÉ-FREMIET

Ciliate infusoria are in general highly resistant to physical changes in their environment, and research indicates that their development is largely determined by the amount of food available. Many of them have developed ingenious and highly specialized mechanisms for capturing and ingesting their food. Their ability to assume a number of different forms at different stages in their life-cycle has often caused confusion and led to the classification of more species than do in fact exist, as Professor Fauré-Fremiet here explains.

Among the protozoa the ciliate infusoria show a very high degree of differentiation and morphological complexity. Almost 120 years ago Ehrenberg described them as organisms in the fullest sense of the word; he erred only when, comparing the structure of these organisms with the smaller metazoa such as the rotifers, he thought it possible to superpose real structural homologies on functional analogies. It needed at first all the knowledge of F. Dujardin to realize that the ciliates, like the rhizopods, are formed of viscous matter, and that therefore they constitute a new kind of structural organization. It then needed the generalizing mind of V. Siebold to identify the sarcode of Dujardin with the protoplasm of H. Mohl, and to regard the protozoa as unicellular organisms. Finally, it needed the critical observations of C. C. Dobell to recognize that the protozoa can be described with greater exactitude as non-cellular organisms.

Owing to the wide range of form, the ciliates can adapt themselves to an equally wide range of habitat. Although it is easy to distinguish planktonic and littoral forms, motile and sedentary species, and those whose feeding habits, though generally phagotrophic, are more precisely described as microphagous or macrophagous or histiophagous, etc., much remains to be learnt about the ecology of these organisms.

In this respect the small size and rapid rate of multiplication of the ciliates allow their populations and their partnerships to develop both in a restricted space and in a short time. This circumstance is very favourable to the study of the interrelationships and interdependencies which are established, not only between the different species of infusoria, but also between them and other organisms of small size, both animal and plant, the whole assemblage forming what we may call a microbiocenosis.

The ciliates are widespread in all aquatic habitats; among other investigations, those of L. Noland, Wang, and Picken show that their margin of tolerance is fairly high in regard to various physico-chemical factors such as light, temperature, pH, salinity, and content of oxygen and carbon dioxide in the water.

It seems therefore that food supply is the chief factor influencing the community and its eventual location within certain limited biotopes. Unfortunately our knowledge of the alimentary physiology of ciliates too often remains uncertain, and the following example will show the ecological significance of this fact. The *Ophryoglenidae* are holotrichous ciliates frequently met with in fresh and salt water, but almost always as rare and scattered individuals whose precise identification is difficult from the descriptions given by earlier workers. Research done in my laboratory by Hélène Mugard shows that the *Ophryoglenidae* have a peculiar physiological cycle which had not previously been suspected. These infusoria are sometimes found in clear water in the form of long and transparent individuals, swimming at great speed, which one is tempted to regard as essentially plankton; in fact they are hunters or beasts of prey. If one of them happens by chance to come near to a wounded organism or to animal débris, a chemotactic stimulus is set up, due to some diffusible organic compound which attracts it towards the wounded tissues; its shape changes suddenly, then it attacks the tissues with a gimlet-like movement, worms itself between the cells and greedily ingests the débris. The satisfied infusorian, now thick and opaque, has become unrecognizable and appears to be another species; it moves slowly away from its feeding place, encysts below the surface, digests its meal, and divides two or three times, forming four or eight swimming organisms similar to the parent, which are soon in quest of food. Such histiophagous ciliates remained for long unrecognized. Observations of their life-cycle *in vitro*

were needed in order to define the species and to grasp the eventual importance of the part they played in the economy of small aquatic communities.

The microphagous ciliates are by far the most frequent and the richest in variety of species. They feed on minute organic particles and bacteria in suspension, which are drawn towards their mouths by means of a current set up by the movement of their cilia. Other species are macrophagous; some are herbivorous, feeding on diatoms, desmids, *Oscillatoria*, etc.; others are carnivorous, feeding on other infusoria. Some of these can tackle large prey, which is often stunned by a discharge of toxic trichocysts before being swallowed; micro-cinematograph records made by J. Dragesco vividly demonstrate their voracity.

It is important to note here that, for a large number of ciliates, both microphagous and pre-datory, the feeding is selective, and that certain prey, whose specificity can be narrowly deter-mined, is essential for the sustenance of a given species. This fact may be associated with some structural peculiarity influencing capture and in-gestion, but it can more often be linked with a biochemical peculiarity.

The elegant researches carried out in the labora-tories of A. Lwoff and of G. W. Kidder on the nutrition of ciliates maintained in sterile culture show, in fact, that many of them have only a restricted power of synthesis. Their maintenance requires the supply of complementary substances, or growth-factors, elaborated either by bacteria, or perhaps by algae, or even by other ciliates. It thus appears that the essential food substances can create conditions of nutritive interdependence, more or less narrowly specific. Such interrelations are generally the beginning of all microbiocenoses.

Different types of associations of which the principal members are protozoans and proto-phytes are formed in fresh water. A relatively simple case is the *Beggiatoa* association. The colourless sulphur bacteria, *Leucothiobacteriales*, often grow as white, velvet-like patches on black mud rich in organic matter and covered by a shallow depth of running water. Their presence shows the pre-existence in the mud of anaerobic bacteria capable of decomposing the organic matter and forming the hydrogen sulphide which *Beggiatoa* uses in respiration. The white patches thus develop as the result of a bacterial association. Their appearance depends on the properties peculiar to the sulphur bacteria, whose long fila-ments move slowly on the surface of the mud, becoming entangled and forming a felted mat, the

contour and thickness of which are regulated by a twofold tendency—surface spread and superficial condensation. The colony of *Beggiatoa* holds water, which is slowly renewed; testing with phenol red at the edge of the colony gives a yellow tint, indicating a *p*H slightly more acid (about 6·8) than that of the aqueous medium. This acidity, due to the metabolism of *Beggiatoa*, produces a chemotactical swarming of two common species of microphagous ciliates, *Colpidium campylum*, and *C. colpoda*, which collect round the colony, pene-trate it, and feed actively upon the small bacteria composing it. From that moment two ecological effects begin to operate—the formation of a food chain and the initiation of the microbiocenosis. The reproduction of these two species of *Colpidium* in this favourable habitat leads to a great density of population; it must be noted that this density is a result not only of multiplication, but also of the statistical equilibrium between the entrances and the exits of the motile organisms which stay a longer or shorter time in the felt of bacterial fila-ments in which they find their food. The two species of *Colpidium* do not disturb each other. Nor does their presence seem to harm *Beggiatoa*— rather the contrary, because the movements of the infusoria ensure renewal of water inside the colony and preserve its shape and activity.

The balance of the association is soon modified by new arrivals belonging to the class of predatory infusoria. These voracious ciliates are usually represented only by widely scattered individuals. Some feed almost exclusively on *Colpidium cam-pylum*; such are *Enchelys mutans*, *Lionotus lamella*, and *Leucophrys patula*. If one of these ciliates enters the neighbourhood of the *Beggiatoa* community it begins to feed on its usual prey, and its rate of reproduction is sufficient to ensure an almost com-plete destruction of the *C. campylum*.

These three predatory species are apparently equivalent and interchangeable if one considers only the effect exercised by one or another on the equilibrium of the original association, but if two of them arrive simultaneously it is no longer so. The experiments carried out by J. Ducornet show, for example, that *Lionotus lamella* is capable of attacking *Leucophrys patula*, and that the *Leucophrys* can swallow small specimens of *Lionotus;* in this case, the prey ingested devours and kills its attacker, so that the contest is generally fatal to the *Leucophrys*. The destruction of *Colpidium campylum* limits the increase of *Lionotus* automatically, by lack of food, and seems to retard indirectly that of *Colpidium colpoda*.
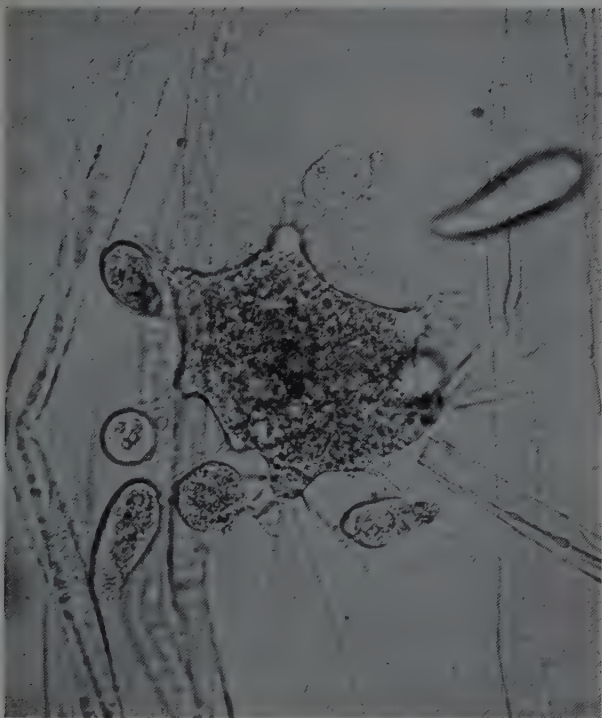
FIGURE I – Trichophrya epistylidis *on peduncles of* Carchesium, *capturing and sucking* Colpidium campylum.
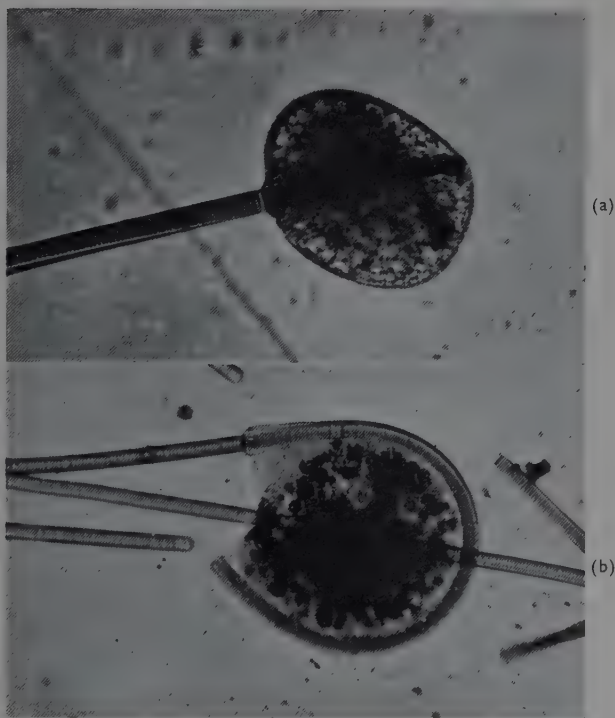

FIGURE 2 – Nassula ornata *ingesting* Oscillatoria. (a) *Beginning of ingestion.* (b) *The body of the infusorian is deformed by the elasticity of the trichome.*

FIGURE 3 – Coleps hirtus *seen in refracted light, after incineration, to show the calcified skeleton.*

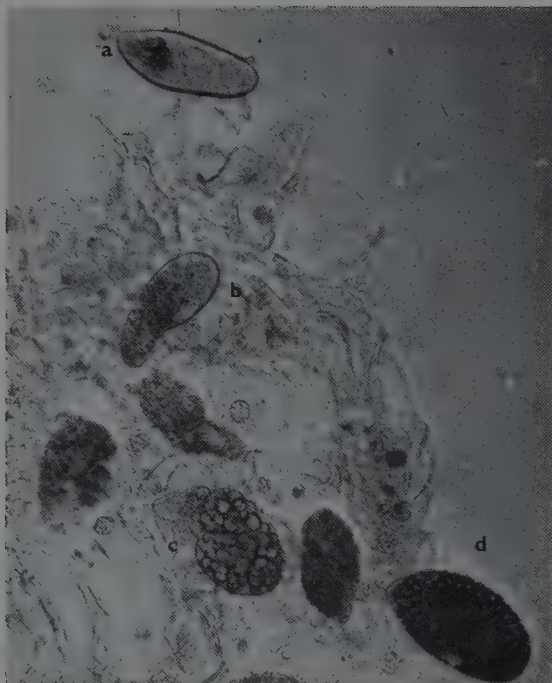FIGURE 4 – Centrophorella fistulosa, *a very large ribbon-like infusorian, characteristic of fine marine sands.*

FIGURE 5 – *An Ophryoglenid*. Deltopylum rhabdoides *attacking the intestinal tissue of a larva of Chironomus.* (a) *A predatory individual coming into contact with the tissue.* (b–d) *Individuals ingesting tissues, seen in different stages of repletion.*
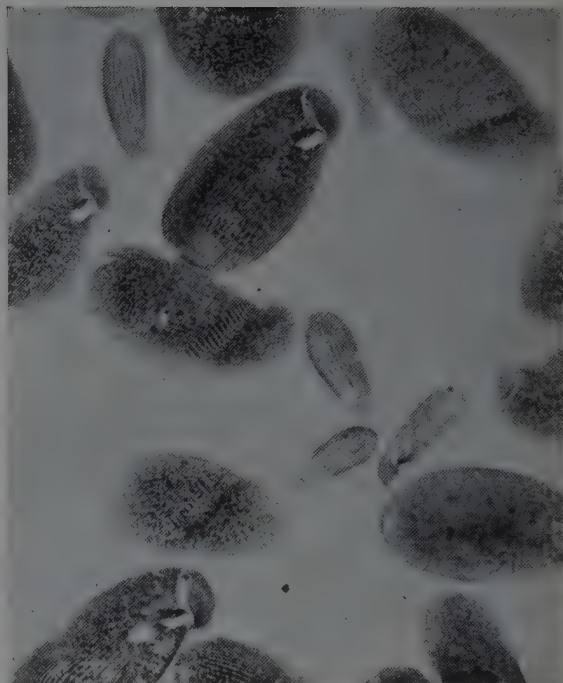
FIGURE 6 – Colpidium colpoda *and* C. campylum. *Cilia stained with silver by the method of Chatton and Lwoff.*
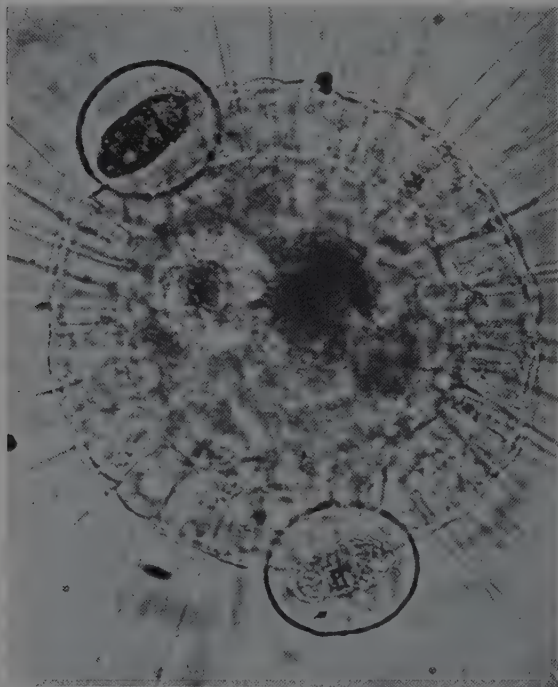
FIGURE 7 – *Two* Coleps *ingested by an* Actinosphaerium, *illustrating the continuation of a food chain.*
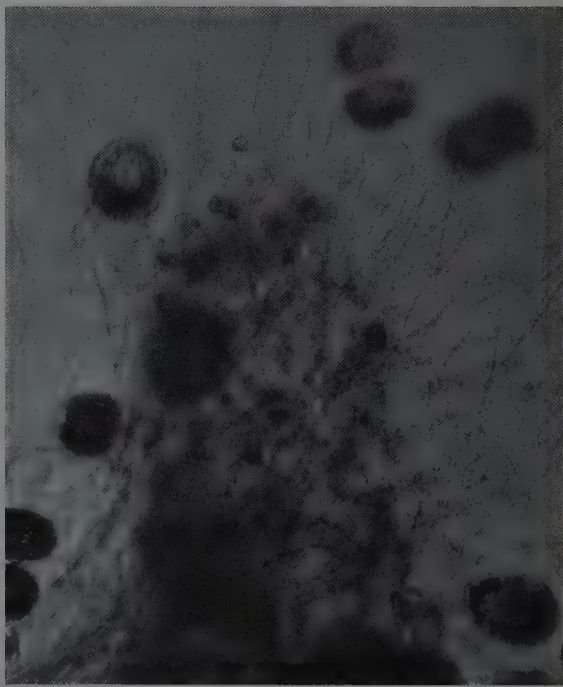
FIGURE 8 – Glaucoma *sp. browsing on* Beggiatoa *'matting.' The accumulation of refringent sulphur grains stains the infusoria deeply.*

It is then that two new species filter into the infusorian colony, already sparse. One is a species of *Glaucoma* which feeds entirely on *Beggiatoa*; the other is *Chilodonella cucullus*, which uses mainly the same sulphur bacteria. These two species thus attack the organic matting which was the mainstay of the association, and, with its destruction, their rapid increase produces the end of the biocenosis, the remains of which are ingested by a ciliate detritus feeder, *Coleps hirtus*, the last occupier, which increases in its turn.

This is not an isolated example. Picken has studied two other types of microbiocenosis, the 'fungus association' in which the organic substrate is formed by the mycelial network of *Sphaerotilus natans*, and the blue-green association of which the substrate is formed by the filaments of *Cyanophyceae*. The basic nourishment, formed in the first case by bacteria and in the second by diatoms, is used by various species of protozoa and, more especially, ciliates which begin various food chains continued by the predatory carnivores. Hence 'the assemblage of protozoa . . . is not a collection of individuals depending directly, for the most part, on one source of food, but a differentiated community of herbivores and carnivores forming, with the basic food supply, a closed social unit.' This conclusion is equally valid for *Beggiatoa*. In each of these biocenoses each of the associated species plays (as Picken suggests) a definite role, or fulfils, one might say, a particular function, the character of which depends on its specific nutritional needs and whose relative importance is bound up with its ability to reproduce. For each type of community the functional distribution of species attains a characteristic social structure. A similar role can, however, be played by several species, which are equivalent and interchangeable, so that the specific composition of an association can vary without modifying the social structure, comparable with the convergence of the food chains in a pyramidal form as described by Elton.

Parallel with their social structure, the associations have a physical structure the characteristics of which depend on the nature of the organic substrate: fungus mycelium, filaments of *Cyanophyceae*, or, in the preceding case, the felted mat of *Beggiatoa*. Picken stresses the important role played by this reticulate structure, which allows

the movement in response to contact-stimuli so common among the protista, and which holds within its mesh a body of liquid forming, so to speak, the inner core of the biocenosis.

The large sedentary infusoria such as *Stentor*, like the branching colonies of *Carchesium*, *Epistylis* and *Opercularia* developed on submerged surfaces, can form a useful organic substratum for certain associations. The strong currents of water set up by the ciliary movements of the zooids drive to the bottom a large number of particles, bacteria, and diatoms. These soon cover the substratum and are used by the various motile ciliates, microphagous or herbivorous, which form the floating population. These in turn are exploited by tentaculate protozoa, the messmates of the colonial vorticellas, or by various special predators, some of which even attack the colonial zooids themselves.

The associations of planktonic ciliates are no less interesting than the littoral biocenoses. In them, also, systems of convergent food chains can be established, but the physical structure of these diffuse associations can almost be compared to that of a solution. The sand-dwelling infusoria (E. Fauré-Fremiet, 1950), and their trophic association with the flagellates and the bacteria, show a similar case in a very different medium; the damp sand of marine beaches, for example, acts as a solvent habitat. The mesopsammon (community between the sand grains) can be compared, in fact, to a solid plankton.

If the ecology of the ciliates is clearly dominated by their food requirements, it must not be forgotten that the astonishing plasticity of these acellular organisms has made it possible for them to assume very varied specific forms, closely suited to the conditions of the habitat. While not stressing this other aspect of the ecological problems, it can be noted that the diluted associations such as plankton, or the sand-dwelling types, are often characterized by species which are morphologically specialized. On the other hand, the littoral associations described previously, which may by contrast be called coacervations (massed communities), appear, in the course of their evolution, as biological units of a higher order, among which one can recognize, with Picken, a certain degree of physiological integration.

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The technique of biological staining

H. GRAHAM CANNON

The importance of staining in studying the fine structure of living organisms is difficult to overestimate. Many structural details of the greatest significance are invisible in the natural material but can be revealed by the skilful use of selective dyes. Research in staining has also resulted in new means of analysing the physiology of cells as well as their anatomy. The accompanying illustrations show some of the striking results which can be obtained.

In the Sheffield (England) Art Gallery and Museum there is exhibited a collection of remarkable lantern slides of marine animals. These are not, as might be expected, pictures or photographs but the actual animals flattened and mounted in Canada balsam. They were made by Dr W. C. Sorby about the middle of the nineteenth century, and will serve as an introduction to this short article on the technique of staining as applied to the study of the microscopical anatomy of both animals and plants. Some of Sorby's specimens retain their natural colour to a large degree. For instance, a small plaice shows all the pattern of its natural pigmentation, but others, such as *Aurelia*, the common jellyfish, are stained, and the stains that Sorby employed are quite entertaining. He used carmine, which is now one of the standard stains used in all elementary classes, but in addition he experimented to a considerable degree of success with all sorts of extracts. He used damson juice and bilberry juice, and one of his most successful stains was port wine. I should think from the colour of the specimens that he used a good tawny port rather than a more mature vintage type. As far as I could ascertain, he did not use the now famous extract of the bark of the logwood tree known to us as haematoxylin. This was first used in 1863, and his specimens are probably of an earlier date.

The scientist who is not a biologist might reasonably ask why Sorby should have taken the trouble to stain his specimens: we can see living animals and so, surely, we can see them when they are preserved. This is not strictly correct, for many animals are almost impossible to see when alive. Living protoplasm, in fact, in its pure state is colourless and transparent. This can be illustrated in a striking manner if a sample of microscopic floating life or plankton is collected, say in Windermere. In the summer there will nearly always be present a water-flea called *Leptodora*.

This form, as a water-flea, is comparatively enormous, for it is half an inch long, yet it can be seen among the other floating life only by the fact that as it swims about it knocks all the other tiny water-fleas out of the way. It is glassy transparent with only one black pigment spot, which is its eye. In order therefore to see its shape and size, we must pickle or 'fix' it. The aim of this fixation is to precipitate the colloidal living matter in as lifelike a condition as possible. Naturally, with the development of microscopical technique there have been discovered a large number of fixatives, all of which have their own good or bad qualities. On fixing a living *Leptodora*—no matter what fixative is used—the body changes from glassy transparency to opaque white. We have, in fact, by the process of fixation merely converted something which was so transparent that we could not easily see its external shape, into a form which is so opaque that we cannot see through it and therefore cannot study its internal anatomy. This opacity can be overcome by removing the water from the specimen and then replacing it by an alcohol, such as ethyl alcohol, and subsequently by some highly refractive oil like oil of cloves or xylol. The specimen then regains its complete transparency. The only parts of it that will be visible are those which contain pigment, or more accurately, those which have retained their original pigmentation through this drastic process of water removal, for during fixation and subsequent treatment many substances in the cells are either broken down or dissolved away.

Unstained specimens mounted as I have described are permanent. They can be mounted in Canada balsam, and there is then no reason to suppose that they will not last for all time—a great point in their favour. Also, it is possible, though difficult, to use them without further treatment for anatomical study. It is only if, by the remotest chance, the refractive index of their substances were
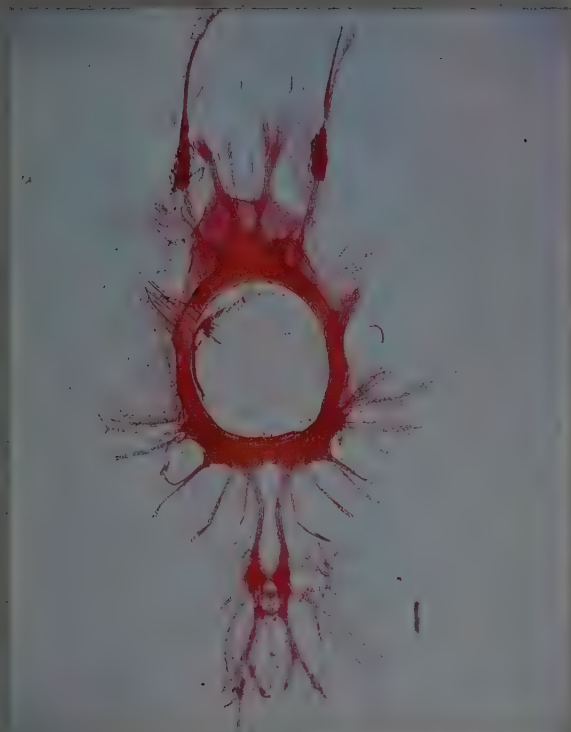
FIGURE I – *A general stain. Nervous system of an Ostracod dissected out and stained in Borax Carmine.*
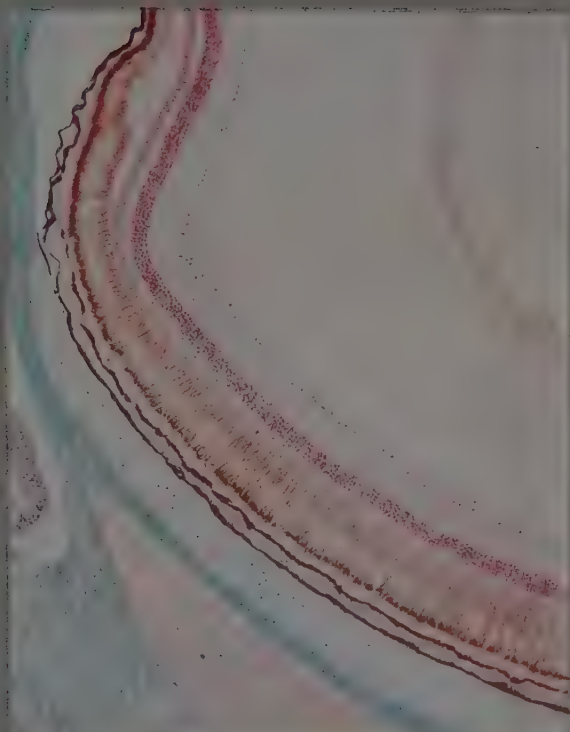
FIGURE 2 – *A triple stain. Section of mammalian retina stained in the orthodox Mallory stain. Cartilage and connective tissue stain blue, blood cells red, and the nuclei of the retinal cells purple.*
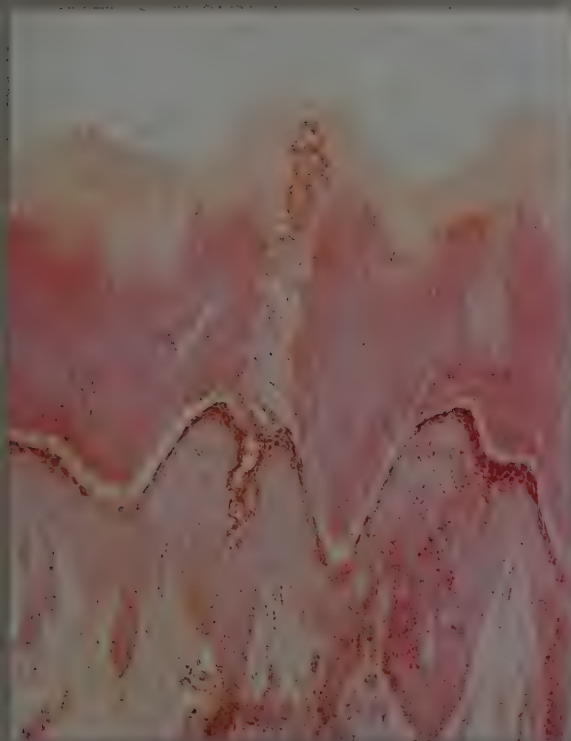
FIGURE 3 – *A triple stain. Section of human skin stained in a modified van Gieson stain. This demonstrates that the outer layer, the* stratum corneum, *is chemically two layers, the outer staining with picric acid and the inner with fuchsin. Inside this are the* stratum lucidum (*picric acid*), *and then the* stratum granulosum

FIGURE 4 – *Section of the skin of a mouse into which Chlorazol Black E had been injected. The histiocytes which have taken up the dye show black against the rest of the section, which has been stained with an orange for the cytoplasm and a red for the nuclei.*

(By courtesy of Dr J. R. Baker, Oxford.)
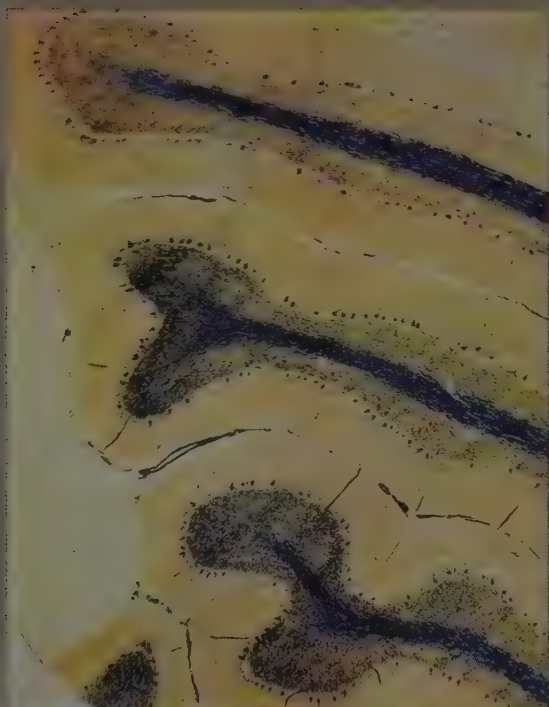
FIGURE 5 – *Section of mammalian cerebellum. Impregnation by silver subsequently treated by gold.*
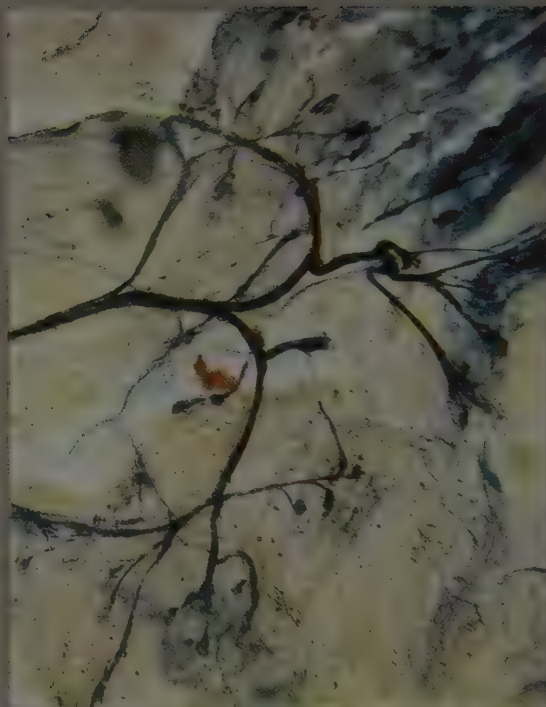
FIGURE 6 – *Impregnation by gold chloride of nerve endings on skeletal muscle.*

FIGURE 7 – *A double stain. Transverse section of the stem of Helianthus, showing lignified cells staining pink with Lignin Pink and the rest of the tissues with Chlorazol Black E.*
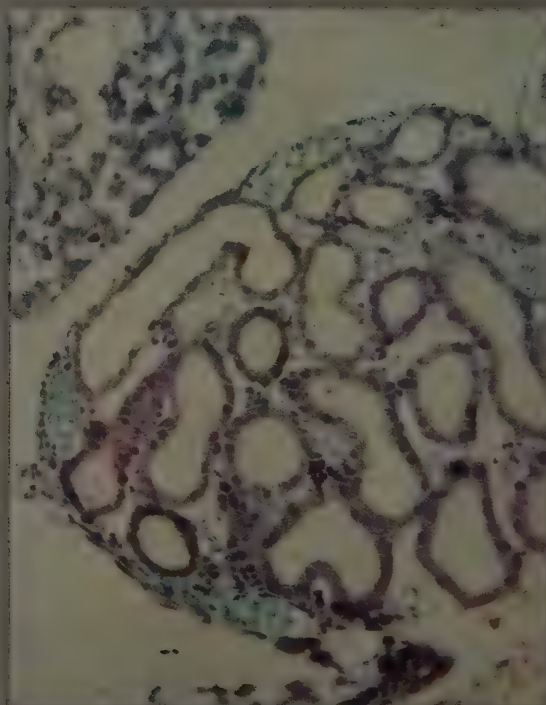
FIGURE 8 – *A double stain. Section of kidney of frog tadpole, showing red blood cells coloured green with Victoria Green and the rest of the tissues purple with Hickson Purple.*

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AUTHOR INDEX

SUBJECT INDEX

SCIENCE, History, and Civilization, EDITORIAL 1

523.112   STEADY-STATE theory of the expanding universe, The, W. H. MCCREA 3

591.2-006.4:575.061.6:597   TUMOURS in fish, Heredity of pigmented, MYRON GORDON 26

081(049.3):52   WRIGHT of Durham, THOMAS, F. A. PANETH 117
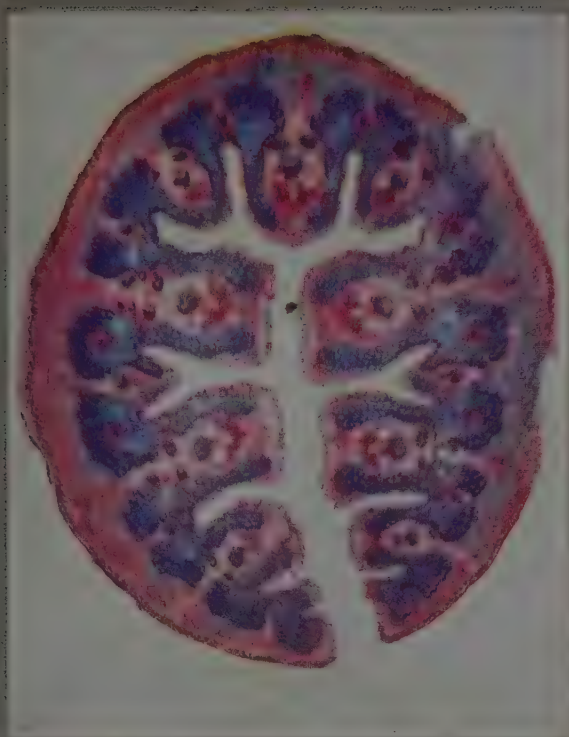
FIGURE 9–*A single stain producing multiple effect. Transverse section of dried esparto grass stained with Chlorazol Azurine.*
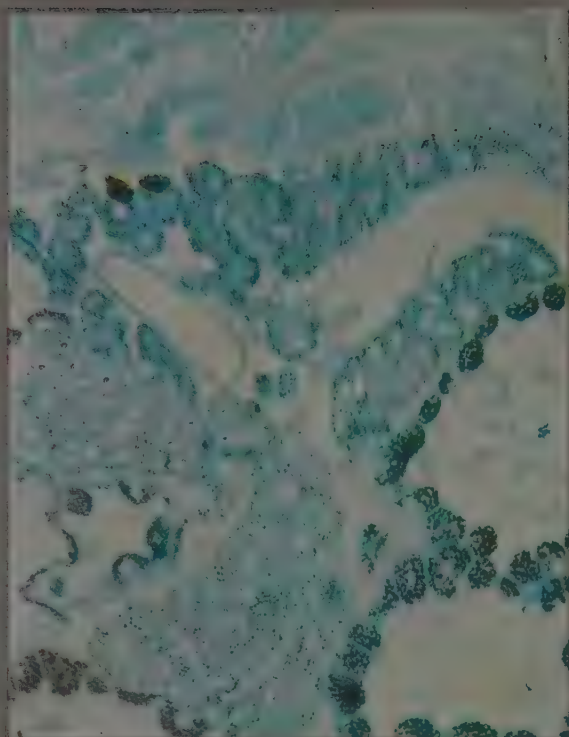
FIGURE 10 – *Staining effect produced by fixation. Fat droplets stained black by osmic acid fixation and the rest of the section double-stained light green and red.* (By courtesy of Professor R. Dennell.)

FIGURE 11 – *A general stain.* Penicillium *stained in Chlorazol Black E.* (By courtesy of Mr F. D. Armitage.)
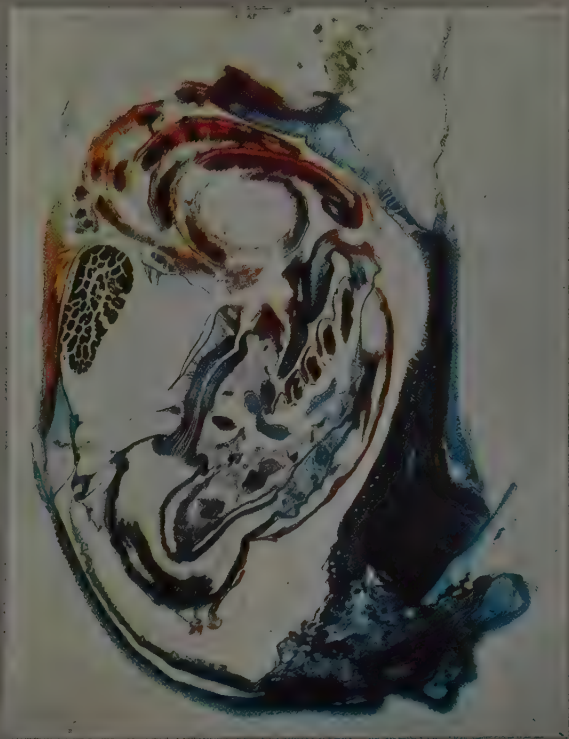
FIGURE 12–*A triple stain. Thick section of a barnacle stained in Mallory after alcohol fixation.*
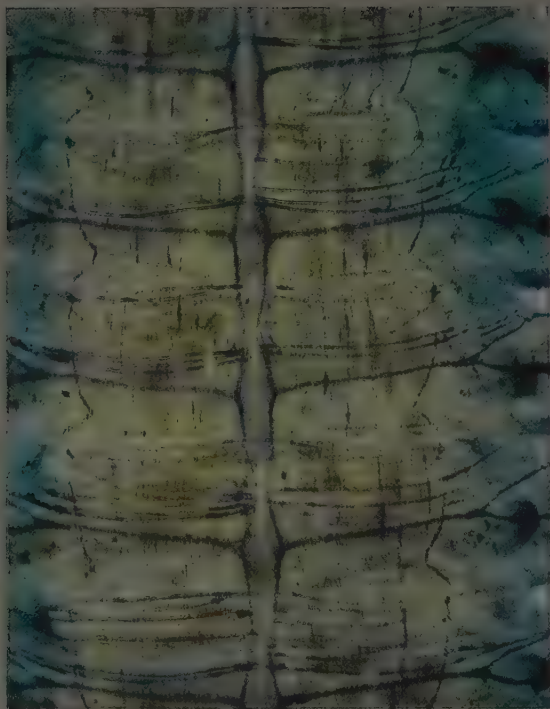
FIGURE 13 – *An* intra vitam *stain, subsequently fixed. Nerve cord of marine worm fixed in I.C.I. zinc-free 'A' methylene blue.*
(By courtesy of Dr J. E. Smith, Cambridge.)
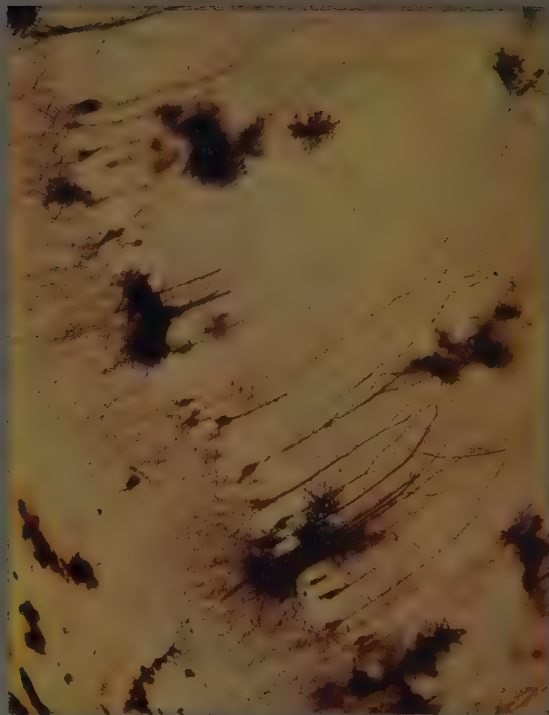
FIGURE 14 – *An impregnation stain. Transverse section of mammalian brain impregnated by Golgi method.*

FIGURE 15 – *A stain to show effect of the solvent. Longitudinal section of the stem of* Helianthus *stained in Chlorazol Black E dissolved in benzyl alcohol, showing the pits in the cell walls stained black.*

FIGURE 16 – *A selective stain. Body wall of barnacle stained for a very short time in Chlorazol Black E in ethyl alcohol, showing elastic fibres stained purplish-black.*

exactly the same as that of the mounting medium that they would become invisible. In all ordinary cases, however, there is a slight difference of refractive index, and, of course, the slightest difference is sufficient to allow for an image to be obtained by critical illumination. That is indeed the whole point. Good illumination is essential and is possible up to a point, but there are limits beyond which the anatomist cannot go and cannot be expected to go. There are some who have maintained that all microscopical anatomy should be done by means of photographs of unstained preparations, using perhaps ultra-violet light. There is no doubt that such a method has yielded very valuable results in a limited field. For the ordinary micro-anatomist, however, and it is as such that I am writing, a good source of illumination and an optimum use of microscope condensers and objectives are all that can be dealt with. After all, a micro-anatomist is in the habit of looking through series of sections running often into thousands, and it is clear that photographic methods can have only an accessory value. He must have an easy and quick method of seeing his structures, and this is provided by staining the whole specimens or sections before they are mounted in their final medium. When this is done they can be seen easily, but it is by their colour rather than by their refractive index. This was, and largely is, the *raison d'être* of staining. Sorby's jellyfish mounted unstained would have been unrecognizable, so he stained them in port wine and at once their anatomy was easily studied. In exactly the same way today, when I begin a study of the anatomy of some minute crustacean, I cut it into thin slices which I then stain so that I can see them easily under the microscope.

Of recent years the technique of staining has developed tremendously. What started as a simple method of making structures visible has now branched out in all directions, leading to valuable methods of analysis of chemical composition and metabolic activity. *The Quarterly Journal of Microscopical Science* is in fact nowadays largely devoted to the most abstruse biochemistry.

I am, however, concerned with the methods used by an anatomist, and what I want to emphasize is that by far the greater part of the staining carried out by biologists is empirical. It does not matter to the micro-anatomist how or why a particular stain behaves in a particular way, as long as it aids him in his study. What does matter to him is that the stain shall always produce the same effect. In other words, it is constancy

rather than purity which counts in a stain. I came across a striking case of this sort after the first world war. A German scientist had described an effect by which the dye alizarin picked out individual nerve fibres in a water-flea. He used a sample of this stain made by Grübler and designated OO: I had some of this particular product and confirmed the experiment, but, when I wanted a further supply, no British alizarin would produce the same effect. In those days, if manufacturing chemists wanted to receive any support from the government they had to produce chemicals as pure as possible. Grübler, on the other hand, saw that as long as he could guarantee to produce the same stain it did not matter to the microscopist using that stain whether it was pure or not, provided that it always produced the same effect. In this case it was clearly an impurity rather than the main chemical which was of value.

In a similar way, Chlorazol Black E was discovered accidentally. It seeped out of a piece of black velvet I was using as a background for the dissection of a small crustacean. Very gradually—in fact after three weeks' intermittent dissecting—it picked out the particular skeletal structures I was endeavouring to see in the unstained specimen, and coloured them a dark green. I therefore boiled a piece of the black velvet in spirit and obtained a black solution which chemists identified for me as Chlorazol Black E. Clearly it did not matter to me why this stain behaved in the way it did. It was a stroke of luck on my part in that I found a solution of very simple use which aided my research.

Subsequently, study has shown that Chlorazol Black E is of very widespread value. Testing it on botanical sections I immediately found that lignified tissue stained the faintest pink. On consultation, a chemical firm produced a pink stain which normally occurs as an impurity in Chlorazol Black E and which is now known as Lignin Pink. Whether the presence of this impurity has anything to do with the general effect of Chlorazol Black E I do not know, but a sample of the latter from which the pink had been removed did not seem so precise in its staining as the ordinary chemical stain.

Again, Dobell, working on entamoebae, showed that the cysts of intestinal amoebae can be identified by staining with Chlorazol Black E. He found that the nuclei and chromatoid bodies stained a sharp black, while the cyst wall stained greyish-green and the glycogen red. Here then is an empirical method of identifying the various types

of amoebae which may occur in the human alimentary canal, a method which incidentally can be carried out in an hour, whereas a day at least was necessary by any other method.

Another peculiar but valuable effect produced by Chlorazol Black E is that its staining properties differ with different solvents. Planktonic forms, such as small medusae and the smaller crustacea, stain quite a different colour when the dye is dissolved in ethyl alcohol from that which they show when it is dissolved in benzyl alcohol. More interesting, however, is the effect on plant tissues. In ordinary ethyl alcohol, Chlorazol Black E stains cell walls black, and the other cell structures various colours from yellow through greenish-grey to black. In benzyl alcohol it selectively stains the pits in the cell walls. In a longitudinal section of the stem of the artichoke *Helianthus* the wall of the pitted vessel appears as a sheet of dark grey spots on a colourless background (figure 15). It is difficult to think of an explanation of this difference, but it is nevertheless a very valuable method of investigating plant structure. As a routine method it has been used in the study of the microstructure of wood by Leighton Hare at Kew (England). This worker, as a routine, mounts three sections, one stained with Chlorazol Black E in aqueous solution, another in ethyl alcohol solution, and the third in benzyl alcohol.

The preparations I have chosen to illustrate this article were made by the ordinary routine types of method employed by the micro-anatomist. The first (figure 1) represents a general stain, and shows the nervous system of a deep-sea crustacean dissected from the body and stained with one of the commonest of all stains, borax carmine. For a general stain, it is not sufficient for the stain to affect all parts equally, as, for example, in the case of eosin, but rather it is essential that while all parts of the tissues are stained, the nucleus should stain more readily than the other parts. With borax carmine this is obtained by over-staining and then washing out the excess stain by acid alcohol, a process called differentiation. In this way a generally pink preparation is obtained in which the grouping of the nuclei can easily be seen, as they remain a dark carmine. Figure 11 shows a simpler case, where Chlorazol Black E dissolved in methyl alcohol has been used as a general stain for the mould *Penicillium*. Here there is no need to over-stain—in fact it is difficult to do so; the stain simply colours the nuclei more readily than the cytoplasm and so the extra process of differentiation is avoided.

It follows from the two cases I have illustrated that it is possible, by differentiation in the case of borax carmine, and by under-staining in the case of Chlorazol Black E, to stain the nuclei only and leave the rest of the tissue unstained. This leads on naturally to those cases where a stain picks out a particular tissue and leaves the rest unstained. Figure 16 provides an excellent example of the selective action of a stain. It shows the elastic tissues in the body wall of the stalked barnacle *Lepas* stained with Chlorazol Black E. In this case the specimen was stained for a short time—just a few minutes—and the elastic fibres stained black almost at once, before the rest of the tissues showed any appreciable staining. In many specific stains, however—in fact, in the majority—the stain affects only one particular tissue or one type of cell inclusion, so that the time that the section is left in the stain is of little importance. Thus mucicarmine is said to be specific for mucous cells, and orceïn for elastic fibres.

Once the idea of a specific stain was established, it was clear that a valuable effect could be obtained by double staining. Thus the Lignin Pink already mentioned is specific for lignified cells. On adding it, therefore, to Chlorazol Black E, a single solution is obtained which, while staining all nuclei and cell walls black, stains the woody tissue a definite carmine (figure 7). The value of this solution is that it does not over-stain and requires no differentiation. A more difficult but even more striking result is shown in figure 8. This is a section of the kidney of a frog tadpole. It was stained first in Hickson Purple, which produced a bluish effect in all cells. Subsequent staining in Victoria Green has picked out the red blood cells, and only these cells, in a definite green.

One of the simplest double stains used in medical laboratories is that of haematoxylin and eosin. In this case the nuclei only are stained bluish-purple, by the haematoxylin, and the cytoplasm of the cells red, by the eosin.

Double staining naturally led to triple and even more complicated methods. Figures 2 and 3 illustrate multiple effects produced by various well-known methods. It must be said, however, that the complicated recipes sometimes put forward for multiple effects are probably often over-complicated. In one case, certainly, which happened in my experience, a senior zoologist got tired of following the elaborate ritual of Mallory's triple stain, use of which is shown in figure 12, and mixed his solutions together. He obtained a very satisfactory staining effect; it may not have been

the orthodox series of colours, but it led to extremely valuable results.

Sometimes a single solution when used by itself will produce a variety of colours. Chlorazol Black E in ethyl alcohol, for example, will stain the chitin of a crustacean limb a dull greenish-grey, while the muscles are given a brownish tinge. A very pleasing effect of this metachromacy, as it is called, is shown in figure 9. This is a section of esparto grass (incidentally taken from a herbarium where it had been dried for many years) stained in Chlorazol Azurine; it shows the vivid red-blue double effect.

Quite early in the history of staining technique, methods were used by which it was sought to impregnate particular tissues, especially nervous material. It was soon found that nerve fibres and nerve cells will take up compounds of gold or silver, which by a subsequent treatment somewhat akin to photographic development can be converted into dark material, and so become visible by contrast with the surrounding colourless tissues (figure 5). Another example given is in figure 6, which shows the nerve endings on vertebrate striped muscle. A more marked effect is the Golgi preparation shown in figure 14, where the individual nerve cells stand out an intense black. While these impregnation methods are very interesting and valuable, it must be remembered that they are capricious; it cannot be predicted which cells, if any, in a block of tissue will produce an effect, and which will be unaffected by the treatment.

The development of *intra vitam* methods, by which living cells take up stain, has made great strides of recent years. Thus, neutral red or methylene blue can be used to pick out particular cells or parts of cells in living tissues. Originally, the difficulty was to fix the cells after they had been stained. Methods have now been devised by which this can be done, and figure 13 shows a very beautiful effect produced by staining the nerve cord of a marine worm with methylene blue and subsequently fixing the stain. The individual nerve fibres are stained a definite blue.

The modern trend of research upon staining is to use this method as a means of analysing the physiology of the cell rather than its anatomy. This is beyond the scope of this short article, but there is one more case which I must mention because it is functional-anatomical. J. R. Baker, of Oxford, showed that by injecting Chlorazol Black E into the body of a mouse, certain cells called histiocytes or macrophages, under the surface of the skin, selected the dye and packed themselves with it so that they appeared black in section (figure 4). This then not only distinguished the histiocytes anatomically, but demonstrated their phagocytic behaviour.

Oliver Heaviside (1850-1925)

It is a seemly thing to praise great men, and most fittingly we celebrate this year the centenary of the birth of Oliver Heaviside, who was born in London in 1850. Heaviside did not receive any systematic schooling in his early years. In 1870, we find him a telegraph operator at Newcastle-upon-Tyne. He never married, but lived with his parents, who had removed to Devonshire in 1889, until their deaths. He later lived in almost complete seclusion in various Devonshire towns. His was by no means a neglected genius; he was elected to the Royal Society at the age of forty-one.

Heaviside's services to the advancement of electrical science were many. He arrived at the concept of a distortion-free circuit in which, by properly adjusting its resistance, inductance, capaci-

tance, and 'leakance,' signals which kept the same form could be propagated along a cable, although attenuated, thus preserving their intelligibility. This operational calculus is internationally used.

His great contribution to electrical science was contained in a series of articles which were published in *The Electrician*. In these articles he developed his theories of wave propagation. Among the important results which he achieved was the prediction of the existence in the upper atmosphere of an ionized layer. This was shown by Dr W. H. Eccles to have important consequences (on account of its different refracting power for wireless waves) in long-distance radio telegraphy and telephony, and Eccles, in 1911, gave to it the name of the Heaviside layer.

Multiple-beam interferometry

S. TOLANSKY

Multiple-beam interferometry offers a delicate method of detecting extremely small imperfections in surfaces. Since highly polished surfaces are becoming increasingly important in technology the method finds many applications, for example in measurements of hardness on a micro-scale by the indentation method, and in studies of the contours of cleavage faces and the nature of cuts made with fine cutting-wheels. The method has proved informative in studying the modes of vibration of electrically excited quartz crystals.

The various techniques of multiple-beam interferometry have now established themselves as methods for investigating the micro-topography [1] and micro-motions [2] of surfaces. In such investigations, it is necessary first to prepare the surface under examination so that it has a high optical reflectivity; it is then matched against a suitably silvered optical flat. If the optical conditions are correct, then, as a consequence of the multiple reflections of beams, very sharp interference fringes can be formed between the surfaces. These sharp fringes are in effect topographical micro-contour lines, and with a correct technique it is possible to measure height-changes on the surface which are as small as one-thousandth of a light wave, i.e. about 5 A. This quantity is less than many crystal lattice spacings, and in fact some cleavage lattice spacings have by this method now been measured with ordinary light waves. It is a characteristic of the techniques that surface details to be examined must not be very small in extension, and an area bounded by a square of side 0·004 mm is about the smallest region that can be accurately studied. The power of the technique lies essentially in the up-down directions, but, despite this restriction, many applications are possible, especially when it is combined with a medium-powered microscope.

It is the purpose of this article to illustrate some of the investigations now being conducted in the author's laboratory, using a variety of multiple-beam interference methods, all of which have been evolved there within recent years.

METALS

The work on metals is in three distinct fields, (a) surface finish, (b) hardness tests, and (c) slip bands.

When surface finish and polish are very high, sharp straight-line fringes are obtained, and, conversely, deviations from the straight line are a measure of the surface roughness. Fine-lapped finishes of metal surfaces are becoming increasingly important in precision technology, and in this field the multiple-beam technique has much to offer as a means of examination of surfaces. Figure 1 shows the fringes given by a typically well-polished stainless steel, the magnification in extension being $\times 300$. The surface irregularities are obvious when it is recalled that, on moving from one fringe to its neighbour, the height has changed by half a lightwave, i.e. about $25 \cdot \times 10^{-6}$ cm.

Figure 2 shows fringes given by a very well polished stainless steel surface with a super-micro finish. In contrast, figure 3 shows the rugged nature of polished aluminium, which, being softer, abrades more easily. Figure 4 illustrates the contours given by rolled sheet steel (tin-plate basis metal), and the rolling grain is very clearly revealed [3]. All these interferograms can be quantitatively evaluated with little labour.

A widely used method for testing the hardness of metals is to make an indentation with a diamond pyramid under known load, and then to measure the superficial dimensions of the indent (Vickers hardness test). Such tests are now often carried out on a micro-scale, using quite small indents—often less than 10 microns across. It was evident that, when the diamond penetrates, the surrounding surface is almost certainly distorted, and such expected distortion-effects have now been studied by interferometry [4]. Figure 5 shows fringes revealing the beautifully symmetrical surface-distortions produced by such a micro-indentation made on a polished steel surface, and this throws light on the mechanism of penetration. Figure 6 shows what takes place when the load is increased. It will be observed that the metal heaps up opposite the sides of the square indentation, but is not greatly distorted in the directions of the diagonals.

When an indentation is made into a single crystal of tin [5], the striking asymmetrical pattern of figure 7 is obtained. The extended wing regions prove to be piled-up hillocks and the short-winged

FIGURE 2 – *Fringes given by stainless steel with super-micro finish.* (× 120)

FIGURE 1 – *Fringes obtained in examination of well-polished sample of stainless steel by multiple-beam interferometry.* (× 300)

FIGURE 3 – *Relatively coarse contours of polished aluminium which, being relatively soft, is easily abraded.* (× 720)
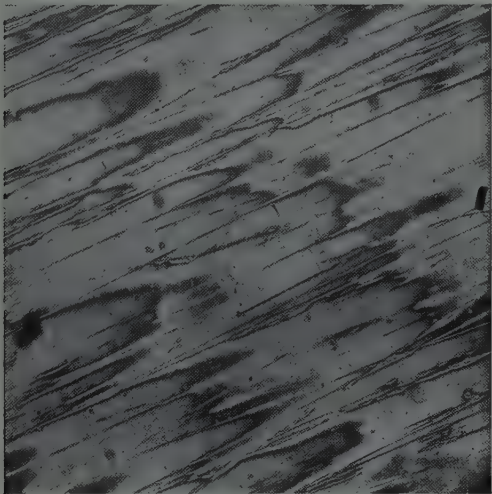
FIGURE 4 – *Fringes from rolled sheet steel.* (× 360)
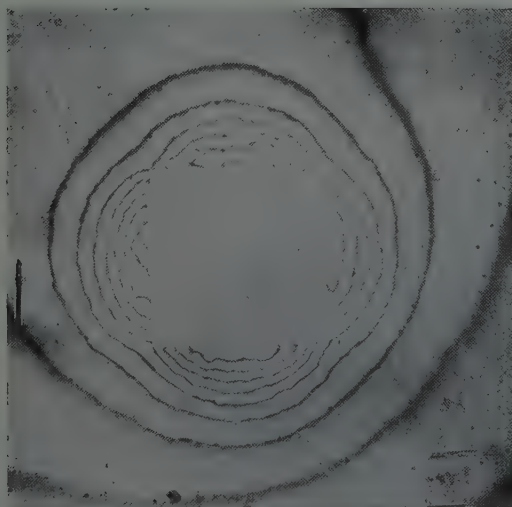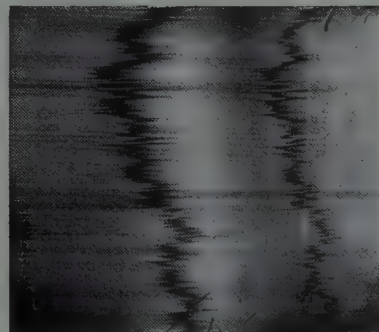
FIGURE 5 – *Surface distortions, produced in micro-scale hardness test, revealed by interferometry.* (× 120)
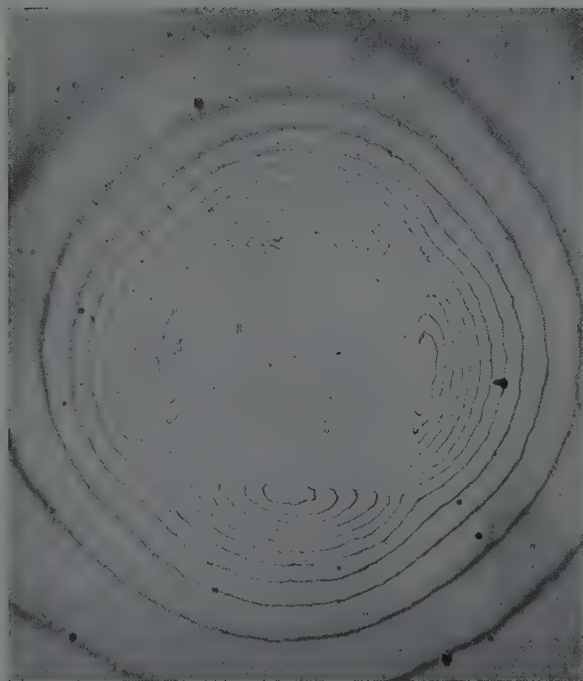
FIGURE 6 – *As figure 5, but with diamond pyramid of hardness test more heavily loaded.* (× 120)
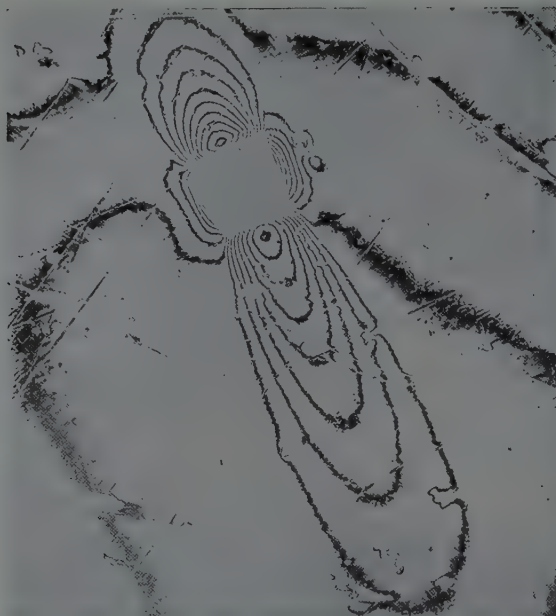
FIGURE 7 – *Asymmetrical contours produced when micro-scale hardness test is carried out on a single crystal of tin.* (× 120)
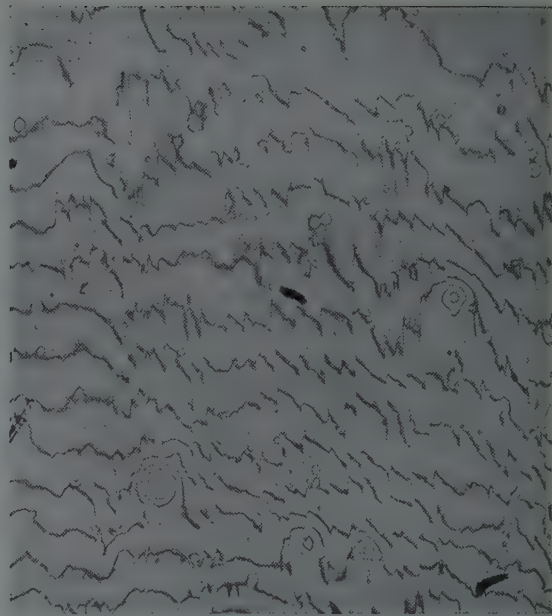
FIGURE 8 – *Slip bands produced by subjecting single crystal of aluminium to tension.* (× 250)

FIGURE 9 – *Picture of fringes superimposed on photomicrograph of slip lines produced in single crystal of tin.* (× 250)
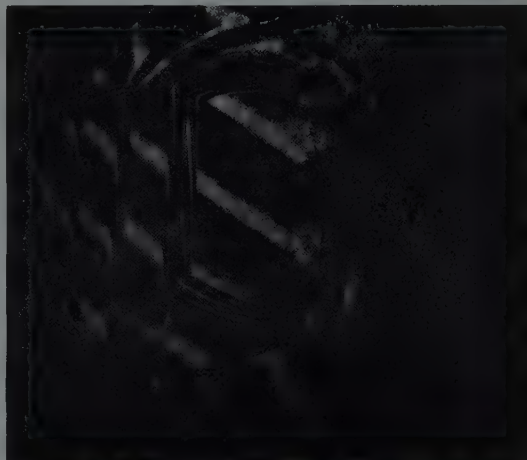
FIGURE 10 – *Contour pattern showing growth sheets on a crystal of beryl.* (× 50)
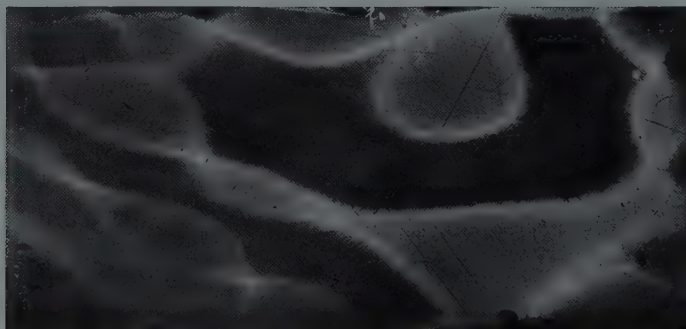
FIGURE 11 – *Interferometric pattern obtained from quartz crystal vibrating at high frequency, showing nodes and antinodes.* (× 10)

FIGURE 12 – *Fringes given by micro-abrasion formed by small rotating wheel bonded with diamond dust.* (× 120)
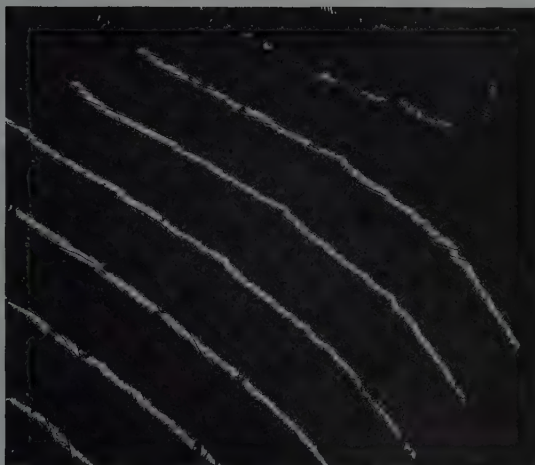
FIGURE 13 – *Fringes given by specially prepared diamond surface. Their sharpness indicates its exceptionally high polish.* (× 25)

FIGURE 14 – *Fringes obtained with vibrating quartz crystal.* (× 10)

FIGURE 15 – *The cleavage planes of diamond are normally complex, but in this example the fringes show an exceptionally clean cleavage.* (× 120)
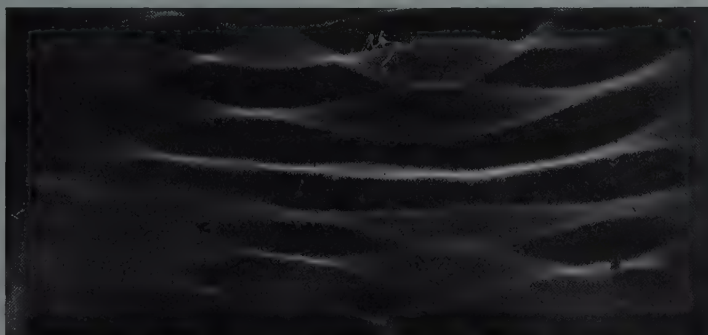
FIGURE 16 – *Fringes obtained with vibrating quartz crystal.* (× 10)
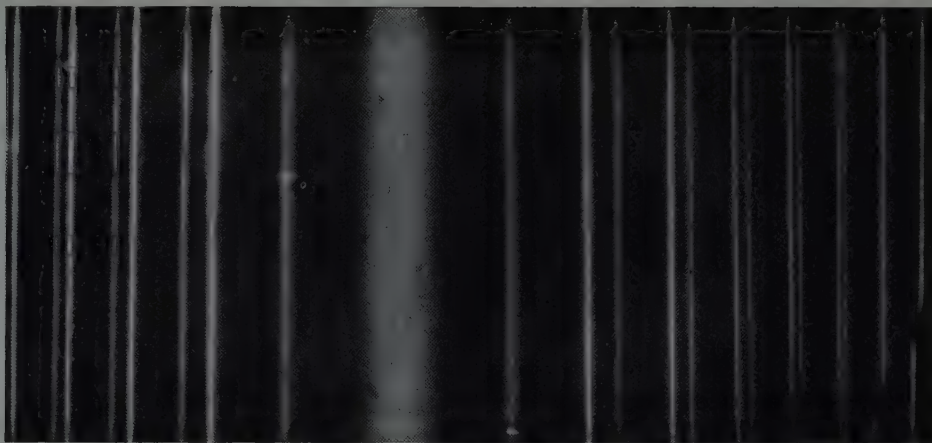
FIGURE 17 – *Fringes produced in a new type of fringe system obtained by means of a sharply curved piece of plane-parallel mica silvered on each side.* (× 10)
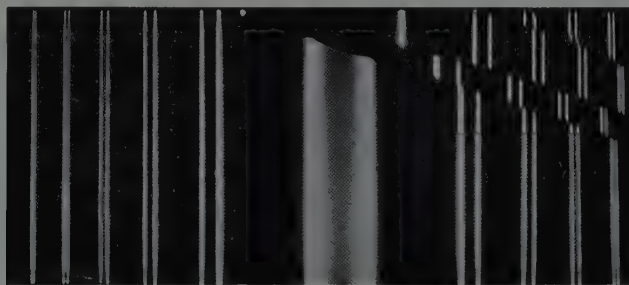
FIGURE 18 – *As above, but using a mica sheet having cleavage steps.* (× 10)

FIGURE 19 – *Fringes produced by two approximately parallel pieces of silvered mica. Brilliant colours result from very slight variations in the thickness of the mica.* (× 10)

FIGURE 20 – *Illustration of the use of interferometry in revealing inclusions in mica which are normally invisible.* (× 25)

regions sunk-in valleys. It has been established that the effect is purely crystallographic, and is directly related to the direction of the crystal axes.

The work on slip bands [6] shows much promise. When metal crystals are strained, the familiar slip bands appear as a succession of close fine parallel lines, and it was evident that by running fringes across a metal surface which had first been polished and then subjected to a slight strain, information about the nature of the slip could be obtained. This has indeed turned out to be so. Figure 8 shows the fringes running across slip bands produced in single crystallites of aluminium when a slight tension has been applied. The step-like formation is rendered apparent, and exact numerical evaluation is an easy matter. Figure 9 shows a compound picture of fringes superimposed on an ordinary micrograph of slip lines produced on a single crystal of tin. Not only does this show the slip, but a marked difference between the aluminium and tin slip phenomena is very clearly rendered. The step-like displacements can be measured with considerable accuracy from such an inexpensive experiment.

CRYSTAL SURFACES

Work on natural crystal surfaces has been deliberately restricted to hard minerals (diamond, beryl, topaz, quartz) because such crystals are more likely to have retained their original surfaces. If the surface of such a crystal has a high natural polish it is not likely to have been weathered or abraded. The crystals examined were selected from considerable stocks for their perfection.

Valuable information on the mechanism of crystal growth has recently been obtained from beryl [7], on which highly complex interference contours have been observed. A typical example (offered here without explanation, owing to lack of space) is shown in figure 10. This reveals interesting growth sheets, which are repaying detailed study.

Much research is being conducted into diamonds, and on these the natural growth features, differential polish directions, and the contours of cleavage faces are all being studied. In particular, directional hardness is being examined by the interferometric analysis of a recently proposed abrasion test [8]. In this test a small rotating steel cutting-wheel, bonded with diamond dust, is applied to the surface with standard load, at a standard speed, for a given time, and a very shallow microscopic abrasion cut is formed. If the volume of this abrasion can be evaluated, then a measure of resistance to grinding and to polishing wear is

obtainable. If the wheel be suitably oriented, the peculiar directional resistant properties of diamond can be studied. Precision interferometry is the only satisfactory way by which these volumes can be determined. Figure 12 shows fringes given by a number of such micro-abrasions [9]. Not only are the shapes and volumes determined, but the fringe definition within the cut shows that the abraded surface takes on an exceptionally high polish.

The ultimate surface finish attainable on a specially polished diamond has been found by interferometry to be surprisingly good. Figure 13 shows the best yet attained, and it will be recognized from the fringe sharpness that a very good optical surface has been obtained. This could be achieved only by repeated use of the fringes as a guide to progress in the polishing technique. High magnification studies reveal a grain structure which proves that there has been no flow during polishing.

Interferometric examination has shown that diamond cleavages are normally highly complex, but one individual fine specimen gave the fringes shown in figure 15. This has yielded to exact numerical interpretation.

OSCILLATING CRYSTALS

Recently [10] some spectacular results have been obtained by applying multiple-beam interferometry to the study of the mechanical oscillations of electrically excited quartz crystals. Crystals oscillating within a considerable frequency range (100,000–3,000,000 per second) have been successfully studied. In these experiments, sharp interference fringes are formed between the surface of a polished quartz crystal and an optical flat. When the crystal is set in oscillation by a suitable electrical circuit, some parts of the surface remain at rest (nodes) and other parts vibrate. A vibration amplitude of even a very small fraction of a light-wave produces a measurable change in separation between crystal and flat. As a result, at the moving regions the fringes broaden out, and thus the whole distribution of surface vibrations becomes clearly revealed, despite the small amplitudes and very high frequencies of the vibrations.

Figures 11, 14, and 16 are typical vibration pictures and obviously reveal a considerable amount of information. Thus, for instance, the distribution of nodes and antinodes is shown, and the amplitudes at the antinodes can be measured with great precision. Irregularities or crystal flaws reveal themselves by anomalies in the pattern. It has been established that some nodes are regions where the crystal is at rest to certainly within less

than 50 A. A stroboscopic technique has also just been developed, in which a fraction of the oscillating voltage is tapped off from the crystal and used to excite the light source for producing the interference fringes. Since source and crystal vibrate at the same frequency, there results a 'frozen' picture of the fringes with the surface apparently at rest. By this means, not only can one measure the nodes, antinodes, and amplitudes, but in addition the instantaneous phases and directions of differential motions over the whole crystal are revealed: for the fringes do not broaden, but twist and bend round the regions which are instantaneously at the same level.

NEW INTERFEROMETRIC TECHNIQUES

A new type of fringe system has been developed [11], and while as yet the interest is purely academic, applications may possibly be evolved later. The mode of production of the system is as follows. A thin sheet of flexible plane-parallel material (e.g. mica) is silvered on both sides, and then bent cylindrically into a curvature of radius perhaps 5 cm. If this is illuminated with parallel monochromatic light a system of very sharp fringes appears, localized in a plane passing through the centre of curvature and perpendicular to the direction of incidence.

An example of such fringes is shown in figure 17. They are quite sharp, and are doubled, the components being mutually perpendicularly plane-polarized, because of the bi-refringent properties of the mica, which in fact produces several highly complex and interesting effects, all of which can be fully accounted for theoretically. If the mica has on it any cleavage steps, they appear within the pattern, as shown in figure 18, and this observation suggests a possible application, apart from the intrinsic optical interest of the system. It is quite easy to put down thin films and layers on to a sheet of mica or some other suitable flexible material, and, on bending, one obtains in effect the equivalent step thickness, representing the thickness of the film.

A new application of an old technique [12] has been the simple adaptation of the familiar principle of superposition, as applied to multiple-beam fringes of equal thickness (introduced many years ago by Fabry). This experiment is a method whereby the slight and normally invisible inclusions in mica, or the small changes of thickness at cleavage, can be revealed with clarity and precision by a simple device. A piece of mica is silvered and then cut in two, the two pieces being held together roughly, approximately parallel. The system is then illuminated with parallel white light, and as a result beautiful colour effects are seen. If the mica had been of perfectly uniform thickness, only a uniform tint would appear, but it is known that mica sheets have slight discontinuities in thickness, which are small cleavage steps varying in thickness and sometimes only a single molecular lattice high (20 A). Owing to the superposition principle, then, even if the mica is fairly thick, one obtains in effect interference over a path-difference represented by the small step, and thus the cleavage areas show coloured regions of uniform tint. One has, in fact, white light fringes of very high sensitivity, although using thick films. Figure 19 (in monotone) gives but a poor idea of the contrasts seen, for splendid colours appear to the eye. A cleavage step only one molecular lattice in height produces a bright change in colour.

Equally interesting is the sensitivity of the system for showing up 'invisible' inclusions within the mica. An example (which again suffers in monotone) is shown in figure 20. Here a small inclusion is revealed, and at the centre can be seen a small included foreign crystal, with a surrounding characteristic region, the contrast arising because of changes in the refractive index of the material.

CONCLUSION

Multiple-beam interference methods are opening up lines of investigation in several distinct fields. The enthusiasm and able participation of the research group in the physics laboratory at the Royal Holloway College are largely responsible.

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Some recent developments in rare-gas discharge lamps

J. N. ALDINGTON

Although the luminous effect produced by the discharge of electricity through gases at low pressures has been known for many years, and the Moore tube was in use as long ago as 1907, the further development of discharge tubes giving light of very high intensity is a quite recent achievement. Originally capable of giving only an intermittent light, very efficient 'gas arcs' have now been constructed which will continuously emit a brilliant white light.

INTRODUCTION

The luminous and other radiations produced by the electric discharge through rarefied air and other gases have been studied for many years. With the notable exception of the Moore tube, introduced in a commercial form in 1907, early gas-filled devices were of little or no value for purposes of general illumination. In view of its historical importance in relation to later developments, it is worth while to consider the Moore lamp in some detail. It consisted in general of a length of glass tubing of the order of 200 ft which was built up and processed *in situ*. The best results appear to have been obtained with tubing $1\frac{3}{4}$ inches in diameter; the colour and efficiency of the light depended on the gas in the tube. In some tubes, nitrogen was used and gave a soft golden light, and in others carbon dioxide, which gave a white light similar to that of the north sky.

Of the rare gases of the atmosphere only neon was found to yield a commercially useful light-source, and, largely owing to the work of Georges Claude, the neon tube for advertising and display purposes became the first rare-gas discharge lamp. It was first demonstrated in 1907, and was the forerunner of a whole range of high-voltage cold cathode discharge tubes which produced a variety of colours; the basic discharge in most cases, however, depended upon either neon or neon-argon and mercury vapour mixtures.

At a later date, fluorescent coatings on the inside of high-voltage discharge tubes were introduced, and the range of possible colours was greatly increased. These lamps in turn eventually led to the mains-voltage fluorescent lamp, which is becoming of considerable importance for general lighting purposes.

During the late nineteen-thirties, the author and his colleagues began a series of investigations involving the passage of heavy current discharges through the rare gases. By 1939, preliminary data had been obtained on discharges in which currents of many amperes were passed through boro-silicate glass tubes about $1\frac{1}{4}$ inches in diameter, containing neon, argon, and helium at comparatively low pressures.

It was found that the spectrum of the radiation was similar to that obtained with the Claude tubes, which generally worked at a current of only 25–50 milliamperes. The efficiency of light production was, however, low, owing to the fact that, although low-loss emissive electrodes were used, the voltage drop in the experimental lamps was only of the order of 30, the arc length being limited to about 20 cm. It was considered that the range of pressure and current conditions which ought to be investigated would require a different type of tube, and probably new circuit techniques, if the obvious possibilities were to be explored in even a preliminary manner. The object was to produce a concentrated-source gas-discharge lamp of high efficiency.

WORK ON CONDENSER DISCHARGES

Notwithstanding the lack of success of earlier attempts to produce a high-efficiency light source using the rare gases, it was felt that the possibility existed of producing a concentrated source provided that sufficient energy could be discharged through the gas. The capacitor discharge technique, for example, had been used successfully for many years for producing short-duration sparks in air. The substitution of a gas discharge tube for the air spark gap was an obvious development, and this method had been investigated by Edgerton and others.

In principle, the method was to charge a capacitor to a high voltage, and then to cause the lamp,

which was permanently connected across the capacitor terminals, to become conductive by the production of an ionizing high-voltage high-frequency discharge on its walls. The conductive state would then build up to a maximum in a few microseconds, and the energy in the capacitor would discharge very rapidly through the lamp.

In early experimental work in the author's laboratories[1] using this technique, boro-silicate glass tubes of various lengths and diameters had a filling of a few mm of argon and a low pressure of mercury vapour. The object at this stage was to produce a very high current density discharge through low-pressure mercury vapour, but a spectroscopic examination of the radiation revealed that very little mercury vapour was present and that the discharge was being carried almost entirely by the rare gas.

It was therefore decided to investigate condenser discharges through the rare gases alone. Some interesting results were immediately obtained. It was found that as the energy discharged through the tube increased, the quality of the radiation changed, and spectrographs revealed that continuous radiation eventually developed at the highest current densities, and that the characteristic line spectrum of the gaseous element in the tube became less dominant (see figure 1). Eventually, tubes were produced in which an inner or guide tube was flanged at each end, but only one of the flanges was sealed into the outer tube. This device was adopted to allow expansion and movement of the inner tube under the shock-wave and temperature-rise which take place when the pulse discharge passes.

It was found that such tubes would carry considerable currents for very short periods of time; some typical data are given in the table below.

TABLE

Type	Joule rating	Approx. lumen sec	Effective duration (microsec)	General use
SF4	400	16,000	450	Scientific purposes
SF5	200	7,000	350	
SF6	100	3,000	200	

It was observed during the course of the work on this type of discharge that the arc did not completely fill the bore of the tubing (see figure 3, which shows a 200-joule discharge through a

[1] Aldington, J. N., 'The High-intensity Flash-discharge Tube,' ENDEAVOUR, 7, 21, 1948.

xenon-filled tube). Such photographs made it possible to measure the approximate width of arc, from which it was calculated that the average current density in the discharge was of the order of at least 1000 amperes per square centimetre.

Observations of this kind, together with measurements of the luminous efficiency of the discharge, indicated that the development of continuous radiation from the flash-discharge tube coincided with the development of relatively high efficiency. Careful measurements of the total flux from the SF4 tube, taken in conjunction with the energy discharged from the capacitor, showed that efficiencies of the order of 40 lumens per watt were possible in the xenon-filled tube, and about 30 l/W in the krypton-filled tube. In each case the colour of the radiation was white, and the distribution of spectral energy was not dissimilar to that of daylight, although there was a predominance of energy at the blue end of the spectrum over and above that present in daylight. Eventually a range of some ten types of tube was produced, and many uses have been found for these repeating flash-tubes, not only of the earlier linear form but also in more compact forms in which the discharge tube proper is wound into a helix of the type shown in figure 2.

The development of a highly efficient white-light source of intermittent character stimulated work on the production of a continuously burning rare-gas light-source of daylight quality and high efficiency, and eventually in 1947 the successful production of the gas arc was announced.

THE GAS ARC

The term 'gas arc' has been applied by the author to rare-gas discharge lamps operated under arc conditions which cause them to emit radiation of daylight quality. The radiation from the gas arc is characterized by an intense continuum extending from the ultra-violet through the visible region into the infra-red. It had been observed previously by the author and his colleagues that, while the low-pressure discharge through argon produced a bluish radiation of low intensity and efficiency, at higher pressures and with very high current densities argon could be excited to produce an intense white light of high efficiency. By comparison with the results obtained in the flash tube, the possibilities with krypton and xenon appeared even more favourable, and it was decided to investigate their behaviour over a range of pressures and current densities. In essence, the problem was to determine whether with available
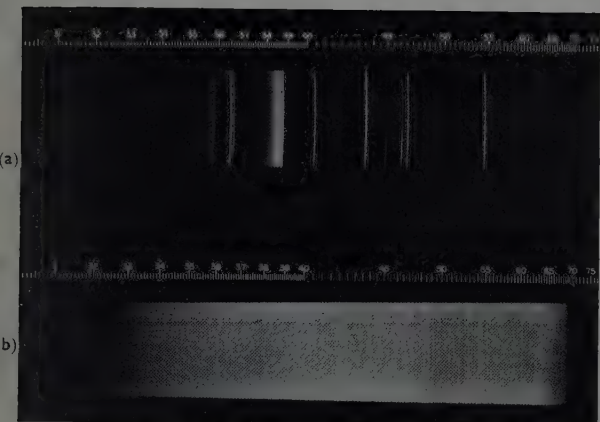
FIGURE 1 – (a) *Low-current discharge through krypton.*
(b) *High-current discharge through krypton.*

FIGURE 2 – *Helix of compact type of flash-discharge tube.*

FIGURE 3 – *200-Joule discharge through xenon-filled tube.*
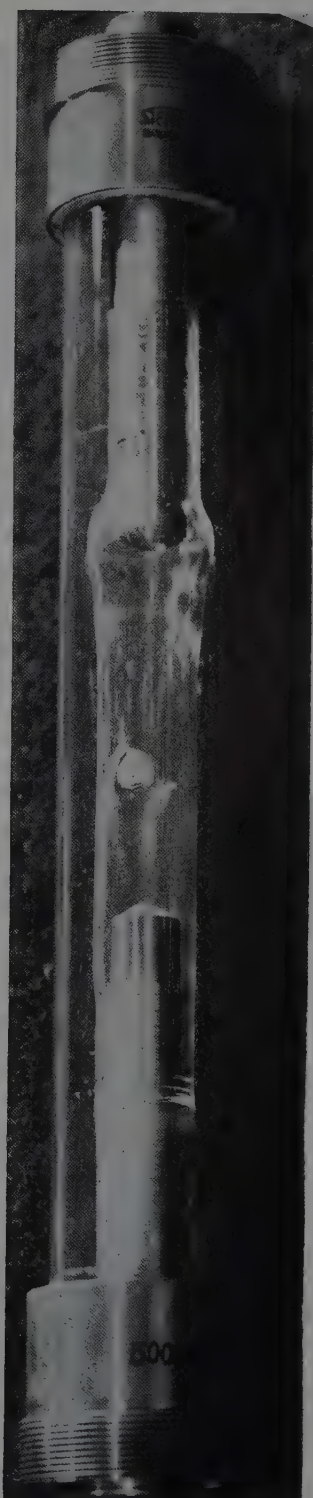
FIGURE 4 – *Complete gas arc in water jacket.*

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materials it was possible to excite the rare gases, either singly or in mixtures, to such an extent that a continuous background spectrum was obtained, and secondly to determine whether under such conditions a practical lamp with a reasonably high efficiency would result.

In considering the development of any discharge tube in which a particular gas has to be hermetically sealed there are a number of obvious but important factors of which it is necessary to take account. These factors include the temperature which will be attained by the walls of the containing vessel, the temperature reached by the electrodes when the discharge is passing, the physical and chemical stability of the electrodes, and the material of the containing vessel exposed to the discharge. The ideal to be pursued is obviously a discharge lamp with an envelope consisting of a transparent refractory substance which will remain completely unchanged under the influence of the discharge; electrodes which suffer little or no sputter or evaporation during life; and a gas-filling which emits its full light output of daylight quality, and at high efficiency, immediately the lamp is switched into circuit.

It was found in the earlier work, and as shown in figure 3, that a constricted discharge occurred in krypton and xenon at quite low pressures. The effect is related to the high atomic weights and low mobilities of these elements. Such a constricted discharge tends to be very mobile, and is easily influenced by convection currents and electrical fields. It was therefore considered necessary for the practical attainment of a suitable discharge that the arc itself should be closely confined, and that convection currents set up in the gas should be restricted by the design of the envelope.

Such considerations suggested the use of a lamp of tubular form and of comparatively high loading. The general considerations outlined above made it clear that the only practicable material for the containing vessel would be quartz. Eventually, for a loading of 5 kW a quartz tube of about 12 mm bore, and with 6·5 cm between the electrodes, was chosen. It was necessary to cool the quartz tube in a stream of running water, and the completed gas arc is shown in figure 4.

The electrodes consisted of polished rods of tungsten containing 5 per cent. of thoria, the ends of the rods being tapered so that the arc was centred on the conical electrode tips. They were designed to fill the inside of the quartz tube closely, and at the ends remote from the arc-space they terminated in molybdenum sealing foils. During the construction of the lamp these foils were sealed *in vacuo* between the outer quartz tube and an inner quartz member, in a manner developed previously for the production of mercury-vapour arc lamps of high current-density.

The gas arc is essentially a high-current, low-voltage device. With a loading of 5 kW the current is of the order of 80 amperes and the arc drop between the electrodes of the order of 65 volts.

In parallel with this work on gas arc lamps of tubular form, experimental work has also been carried out on air-cooled gas arc lamps made from quartz and filled with xenon, similar to certain high-pressure mercury vapour lamps. If the distance between the electrodes is made quite short—of the order of 15 mm—it is possible to obtain an arc brightness of the order of 25,000 candles per square centimetre with a loading of 3 kW.

PROPERTIES OF THE GAS ARC

The water-cooled xenon-filled gas arc with a loading of 5 kW has an efficiency of about 30 l/W. A similar efficiency has been obtained with short arc-length air-cooled forms, and efficiencies as high as 40 l/W have been obtained with experimental linear forms of air-cooled lamp, designed in such a way that the arc voltage was of the order of 100.

The gas arc has a positive volt-ampere characteristic, but it is desirable to operate it in a similar way to other electric discharge lamps, namely in series with a current-limiting device, such as a resistance for direct currents or a reactance for alternating currents. When the lamp is in operation, the current can be varied over a wide range, and an important characteristic is the fact that, with change in arc current, there is only a second-order change in the colour of the radiation.

Compared with other light sources the gas arc has the following characteristics:

1. Excellent colour (similar to that of daylight).
2. Comparatively cool radiation (owing to the water-cooling).
3. Immediate attainment of full light output.
4. Considerable concentration of the light source (the water-cooled 5 kW gas arc has an average brightness of 5000 candles per square centimetre).

Of these properties, perhaps the most important is the fact that in the gas arc we have a light source which can be switched on and off at will, and in which full light output of daylight quality is immediately attained.

Gay-Lussac (1778-1850) as chemist

K. R. WEBB

The early development of chemistry owed much to a spirited and productive competition between the chemists of France and Britain. Among the many distinguished men of the time Gay-Lussac, who died one hundred years ago, stands very high. Davy, indeed, his great British contemporary, said that he would place Gay-Lussac 'at the head of the living chemists of France,' a place to which his formulation of the law of gaseous combining volumes would alone give him a strong claim. He also did much work on physics.

One day in the early twenties of last century a visitor to Paris, calling at one of the foremost chemical laboratories of Europe, might have beheld a middle-aged bespectacled Frenchman of generally grave demeanour engaged in waltzing round the laboratory with a good-looking but rather bewildered young German. The elder was Joseph Louis Gay-Lussac, the greatest living French chemist; the younger was Justus von Liebig, later to be professor at Giessen and Munich and a founder of the nineteenth-century German chemical school. Gay-Lussac was celebrating, in the poetry of motion, a successful investigation by Liebig into the nature of the fulminates, carried out under his direcion [1].

Joseph Louis Gay-Lussac was born at St. Léonard-le-Noblat, about fourteen miles from Limoges, on 6th December, 1778, the son of a legal official who was also a local landowner [2]. To the family name of Gay had been added that of the village, Lussac, where the property was situated. Because of the distracted state of France during his early years, the boy was educated at home by a cleric, the Abbé Bourdeix, until the time when the ecclesiastics were expelled, and it was not until November, 1794, that he was able to go to Paris to begin formal study for the admission examination to the *École Polytechnique*. During this period he was a high-spirited youth, and in his later, more sedate, days he astonished his friends

Gay-Lussac

by tales of boyish escapades, in which he was usually the leader, and which generally had some such object as raiding an orchard [3].

Even in 1795 conditions in the capital were none too tranquil, and the story is told of young Gay-Lussac, armed with a large sabre, accompanying his landlady into Paris from the rural outskirts where they lived, when she took in for sale a cartload of milk each night. On the return journey in the early morning, her escort lay in the bottom of the cart, studying geometry or algebra.

Gay-Lussac's studies were fruitful, and on 27th December, 1797, he was admitted to the *École Polytechnique* after a brilliant performance at the examination, and having successfully completed the course there—during which he found time to give mathematics lessons to augment the state grant of 60 francs a month—he left the school on 22nd November, 1800.

He was already marked out for fame, and having assisted Fourcroy and acted as demonstrator to Berthollet, who observed his quickness and intelligence, Gay-Lussac was transferred to Berthollet's private laboratory at Arcueil, there to begin his research career with investigations on the physical properties of gases and vapours. In 1802 he published his first paper, on the thermal expansion of these bodies. Other physical studies occupied his attention at this period, involving

work on vapour pressures, thermometry, hygrometry, eudiometry, and the measurement of capillary effects, in which he seems to have been a pioneer in the use of the cathetometer.

During 1804, in conjunction with Biot, he engaged in aerostatic adventures of a spectacular sort, though with strictly scientific intent. The purpose was to discover whether magnetic forces persisted above the earth's surface. In the first ascent they found no diminution up to 4000 metres—the best the balloon could do with both men on board—and in a later ascent, on 16th September, 1804, made by Gay-Lussac alone to over 7000 metres (the highest attained up to that time), he confirmed the earlier findings and brought down specimens of air for analysis. During this ascent, having reached 7016 metres and wishing to ascend still higher if possible, Gay-Lussac jettisoned a few objects to lighten the balloon. A shepherdess was amazed to see a white wooden chair come hurtling down into some bushes, but the realist peasants who heard her story were at a loss to correlate its suggested celestial origin with its evidently crude workmanship [4].

Gay-Lussac and Biot making their balloon ascent

On 12th March, 1805, Gay-Lussac set out from Paris with Alexander von Humboldt, recently returned from his famous American travels, for a scientific expedition into Italy and Germany. They arrived in Rome early in July, and here, in the house of Wilhelm von Humboldt, the Prussian minister, the youthful *savant* enjoyed the company of various notables in the artistic and scientific worlds, and, having a laboratory at his disposal, discovered the presence of fluorides as well as phosphates in the bones of fish. Later, the travellers moved on to Naples, where Vesuvius, previously quiescent for some time, suddenly reasserted itself, so that, in the words of one of his companions, Gay-Lussac had the happiness to experience one of the most memorable earthquakes ever known in that region. On the return journey, pauses were made at Florence, Bologna, and Milan, where they visited Volta—whom they had some difficulty in finding, as he lived modestly

in obscurity. Arriving during November in Berlin, Gay-Lussac stayed there as von Humboldt's guest throughout the winter, and finally returned to Paris in the spring of 1806. On 8th December, 1806, he was elected a member of the *Institut de France*, in place of Brisson, the physicist and natural historian.

In 1807, Gay-Lussac became one of the first members of a select scientific society—the *Société d'Arcueil*—founded by his early patron, Berthollet. In the second volume of its *Mémoires* (that for 1808) occurs a paper, read on 31st December, 1808, announcing for the first time the outlines of Gay-Lussac's law of gaseous combining volumes, one of the foundation stones of early chemical theory.

About this time Gay-Lussac began his fruitful collaboration with Louis Jacques Thenard (1777–1857) [5], of which more will be said later. Also in 1808 he married Joséphine Rogeot, whom he

had first met as an assistant in a linen draper's shop in Paris. This girl of 17 was, he observed, engaged in reading a treatise on chemistry during her spare moments. It turned out that Joséphine's education had been disturbed by the aftermath of the Revolution, so Gay-Lussac had her interrupted schooling completed and they then married. It was an ideal match, although at the time Joseph had no position of importance. This was, however, just round the corner, for soon afterwards he became professor of physics at the Sorbonne, and on 31st March, 1809, professor of practical chemistry in the *École Polytechnique*, and full professor on Fourcroy's death in 1810.

Gay-Lussac and Thenard had first met as fellow-students at the *École Polytechnique* in 1798; in 1808–9 they began work together, using a gigantic electric battery provided for their use by Napoleon himself, in an endeavour to surpass the brilliant discovery of the alkali metals by Davy in 1807. Before the battery had been assembled, however, the two Frenchmen discovered an alternative, and at that time more efficient, means of decomposing the alkalis, viz. their reduction in a molten state by white-hot iron. Using potassium so prepared they reduced boric acid, a preliminary note being read on 21st June, 1808. Such pioneer work was not unaccompanied by dangers, and Gay-Lussac was seriously injured by an explosion on 3rd June, 1808, involving potassium, in which he almost lost his sight and from the effects of which his eyes permanently suffered. By the end of 1808 the new element, boron, had been pretty well characterized; it should be said that Davy also did much independent work in this field.

In addition to their use of the alkali metals in this way, Gay-Lussac and Thenard also studied their oxidation and prepared their higher oxides, as well as those of barium and calcium [5].

About this time, too, occurred the famous controversy between Gay-Lussac and Thenard and Davy concerning the nature of chlorine, then called oxymuriatic acid and believed to contain oxygen. Davy's experiments showed conclusively that the gas contained no detectable oxygen, and that in all its reactions it behaved as an element. The Frenchmen, adhering to Lavoisier's view that muriatic (hydrochloric) acid must contain oxygen as the acidifying principle, considered that chlorine, a product of its oxidation, must of necessity also contain oxygen. Eventually, the correctness of Davy's views became clear, and so there vanished from chemistry the outmoded 'oxygen theory' of acids [6].

In 1812, iodine, the second of the halogen elements to be isolated, was discovered by Courtois. Soon after the publication of his discovery, both Davy and Gay-Lussac were independently engaged on an investigation of the substance and its derivatives. The result of this work was the establishment of iodine as an element, and by August, 1814, Gay-Lussac was able to present to the *Académie des Sciences* his completed 'Researches on Iodine.' He contributed also to early fluorine chemistry, for in 1809, in collaboration with Thenard, he first prepared a reasonably pure specimen of concentrated aqueous hydrofluoric acid. The crude material had been obtained by Scheele in 1771 [7].

In 1815, two very important pieces of work were done. Already, in 1811, Gay-Lussac and Thenard had introduced potassium chlorate as an oxidizing agent in quantitative organic analysis. This substance proving rather violent, Gay-Lussac, in 1815, substituted for it the more moderate copper oxide, especially for the analysis of nitrogenous substances. Very soon, Döbereiner applied copper oxide universally in place of the chlorate, with great success. Also in 1815, Gay-Lussac discovered cyanogen, the first compound radical to be isolated. Prussian blue was described as early as 1704; from it Scheele in 1782 had obtained, by distillation with sulphuric acid, an aqueous solution with a 'peculiar smell and taste'(!). This was named prussic acid by Lavoisier, de Morveau, Berthollet, and Fourcroy in 1787 [7]. In 1811, Gay-Lussac obtained the anhydrous substance by distilling mercuric cyanide with concentrated hydrochloric acid, and, in 1815, he isolated cyanogen itself by the thermal decomposition of mercuric cyanide. He showed the general chemical analogy between cyanogen and chlorine and iodine.

The next year, 1816, saw the publication of his paper on the oxides of nitrogen, important for its account of the analysis of nitrogen dioxide. Some years earlier he had determined the composition of nitric oxide by burning metallic potassium in the gas. Three years later, in collaboration with Welter, he discovered and investigated aqueous dithionic acid.

About this time, Gay-Lussac began to be increasingly occupied in the development or modification of processes of importance in chemical technology. In 1806 he had been made a member of the consultative committee of arts and manufactures. In 1818, he became superintendent of the government powder factory; in 1829, chief

assayer at the Mint; and in 1832, professor of general chemistry at the Museum of Natural History, whereupon he resigned from his chair of physics at the Sorbonne.

In 1821, Gay-Lussac showed that wood is made non-inflammable by impregnating it with various inorganic salts, such as borax or ammonium phosphate, which can be readily prepared in quantity. The Gay-Lussac tower for the absorption and conservation of nitrous gases in the lead chamber sulphuric acid process was introduced in 1827, the result of a sudden flash of inspiration on Gay-Lussac's part; indeed, it has been said that the idea presented itself to him overnight, and that, with the aid of an assistant called Lacroix, he had shown its practicability on a small scale by early next morning [2].

Gay-Lussac's great services to analytical chemistry were of fundamental importance, since he must be regarded as the chief founder of the volumetric method. In 1806, Decroisilles had substituted measurements of volumes for those of weights in the determination of alkali by acid; however, Gay-Lussac, while preserving the principle, greatly simplified the operations involved by the invention of his burette (a pouring instrument, different from the modern instrument with clip or tap, introduced later by Mohr), and applied the method not only to acid-alkali titrations, but also to the determination of chlorine in bleaching powder using arsenious acid solution (1824, 1835), and later to the determination of silver by a standard solution of sodium chloride (published fully during the eighteen-thirties).

Two other pieces of work are perhaps deserving of mention; they were his discovery (1829) that an oxalate results from the interaction of fused alkali with wood, a discovery afterwards put to practical use in the manufacture of oxalic acid, and his investigation of the volatile products evolved from *aqua regia* (1848); this was his last published work.

Gay-Lussac entertained what were, at the time, remarkably advanced and far-sighted ideas about the state of salts in solution, ideas which became a part of chemical theory only towards the end of the nineteenth century with the development of the work of van't Hoff and Arrhenius; indeed, he must be considered as one of the founders of modern physical chemistry. These ideas appeared in his article on cohesion, published in 1839.

Gay-Lussac's character and temperament have been sketched by various contemporaries. Very early, Berthollet said to him, 'Young man, your destiny is to make discoveries.' Davy, about 1813, contributed a telling thumb-nail sketch: 'Gay-Lussac was quick, lively, ingenious, and profound, with great activity of mind, and great facility of manipulation. I should place him at the head of the living chemists of France' [8]. This, from Davy, was praise indeed. Another British tribute came from the toxicologist Sir Robert Christison, who attended Gay-Lussac's lectures in 1820 and was much impressed by his handsome and amiable appearance and gentle though firm voice. Christison describes his lectures as 'a superlative specimen of continuous unassailable experimental reasoning' [9].

Another estimate (by Ferguson, not a contemporary) is perhaps more detached if rather less sympathetic: 'Gay-Lussac was reticent, patient, persevering, accurate to punctiliousness, perhaps a little cold and reserved, and not unaware of his great ability. But he was also bold and energetic, not only in his work, but equally so in defence and support of his friends. The endurance he exhibited under the laboratory accidents which befell him showed the power of will with which he could face the prospect of becoming blind, and useless for the prosecution of the science which was his very life' [10].

On 1st January, 1850, Gay-Lussac was taken ill at Lussac, whither he frequently retired in his later years and where he had a house with a laboratory and library. After about two months, he was moved to Paris during a brief respite in his sufferings, and there he died of a heart disease on 9th May, 1850, in his seventy-second year [2]. As long as the principles of chemical science are taught, Gay-Lussac will never be forgotten; with Lavoisier, Dalton, Berzelius, and a handful of others, he is an immortal of chemistry.

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Book reviews

TREATISE ON ZOOLOGY

Traité de Zoologie (Anatomie, Systématique, Biologie), *publié sous la direction de Pierre-P. Grassé. Tome VI. Onychophores, Tardigrades, Arthropodes (généralités), Trilobitomorphes, Chélicérates. Pp. 979. Tome IX. Insectes (Paléontologie, Géonémie, Insectes inférieurs et Coléoptères) Pp. 1117. Tome XV. Oiseaux. Pp. 1164. Masson et Cie., Paris. 1949–50. 5000 francs, 4500 francs, and 6000 francs respectively.*

The first volume of this series to appear set a very high standard, in both production and matter. These latest additions maintain or surpass it. They remain as well produced and printed as their forerunner, enhanced by splendid colour plates, particularly in Volume VI, and clear, well-printed photographs in Volume XV. Unfortunately the increase in excellence has brought with it an inevitable increase in price. It is, however, gratifying to find the volumes appearing so rapidly; for certain sections of such a work must fall out of date in a very few years. The early volumes of a series stretched over a long period would therefore have deficiencies before the completion of the whole work.

Once again the sections are each written by acknowledged experts in their subjects. The result is an all-embracing work covering most of the possible aspects of the anatomy and life-histories of the groups, combined with valuable discussions of their inter-relationships and past history. This is particularly useful in the general discussion of the Arthropod phylum in Volume VI, and in the consideration of the collection of groups with doubtful affinities which makes up the rest of the volume. The theory of continental drift is rightly introduced in the section on the palaeontology and distribution of insects, and a thorough account of the various theories of the origin of bird flight is also given.

It is in the very completeness of these volumes that their failing, if indeed there is any, must lie. To give a full history of the orders, both ancient and modern, with a full description of their behaviour, embryology, physiology, ecology, and economic importance, would be a monumental task. Inevitably, parts of this scheme must be condensed. Pride of place is given, not unnaturally, to the anatomy of the animals. Other sections take their place

according to their importance in a general scheme of zoology and the amount of knowledge available on the subject. A good balance is generally kept. Volume XV is an excellent example. Here a detailed and up-to-date description of avian experimental embryology is included with a review of the vast accumulation of work on the behaviour of birds and their reproductive cycles. In addition, a concise account of bird flight, the mechanics of the bird skeleton in general, and all the morphological and historical detail of the group, are given. Sometimes the non-morphological sections are almost too concise, as, for example, in the sections on bird migration, the insect cuticle, and stridulation in grasshoppers. It must be admitted, however, that their brevity lies laudably in a rigid selection of the best of the most modern work, the references to which form an adequate basis for deeper study. The importance of the sections depends, of course, upon the view point of the reader.

As standard works for general reference these volumes take their place in the front rank, unblemished by their occasional, but often rather delightful, misprints, and sometimes puzzling internal chapter references.

J. D. CARTHY

PHYSIOLOGY OF VISION

Recent Advances in the Physiology of Vision, *by Hamilton Hartridge. Pp. 412. J. and A. Churchill Limited, London. 1950. 25s. net.*

As the author remarks in the preface, five important books have been published in Britain in the past five years dealing with this topic. Professor Hartridge, director of the vision research unit of the Medical Research Council, adds to these a review of recently published work, comments on the theories of its authors, and sometimes offers his own alternative interpretations. The book is divided into eight main chapters, each dealing generally with a different function of the eye, e.g. investigations of retinal function, the perception of shape and size, the perception of colour, and theories of colour vision. Other chapters are devoted to the neurology of vision, properties of the structures of the eye, the appreciation of light and colour, and some basic properties of vision.

In describing experiments and their results Professor Hartridge writes with all his usual lucidity; when discussing

theory, however, impartiality demands that all points of view should be mentioned. The treatment in this book occasionally tends to blur the general picture, since the theories (of colour vision, for example) are often quite numerous. One of the author's express purposes is to stimulate further research by pointing out gaps in our knowledge, and in this way the book will undoubtedly be very valuable to the research worker and specialist. It will be less so to the student, until he has some acquaintance with the subject.

The nature of many of the problems remaining to be solved suggests that striking progress in research would follow an intensive application of the delicate techniques now made available by advances in electronics and nuclear physics.　　J. M. M. PINKERTON

CYTOLOGY

La Cellule: Principes de Cytologie générale et végétale, *by R.-J. Gautheret. Pp. 404. Albin Michel, Paris. 1949. 960 francs.*

This excellent book should be particularly valuable at the present time, when so many interesting researches on the cell are being made by investigators who have scarcely any background of general cytological knowledge. The whole field of cytology is covered without undue emphasis on any particular part. In this, the book is unique among modern textbooks of the subject. In a work of moderate size it is not possible to enter deeply into any particular aspect of the subject without upsetting the balance, and the author carefully avoids this pitfall. Not every specialist will approve of every section of the book. For instance, the explanation of phase-contrast microscopy is not quite satisfactory, and the description of the interphase nucleus will not find universal acceptance. In general, however, the information given is reliable, debatable points are handled judiciously, space is not wasted in the discussion of hypotheses, and the whole exposition is an admirable example of French logic and clarity.

Many cytologists have a primarily botanical or a primarily zoological outlook; many are either students of the nucleus or else concentrate on the cytoplasm. Professor Gautheret's wide outlook and level judgment serve well to draw together the apparently disconnected constituents of what should be a single science.　　JOHN R. BAKER

SOIL SCIENCE

Soils, their Physics and Chemistry, by A. N. Puri, with a foreword by Firman E. Bear. Pp. xv + 550, with line diagrams. Reinhold Publishing Corporation, New York; Chapman and Hall Limited, London. 1949. 56s. net.

Prospective readers of this book must not assume from its title that it is a textbook. It is an exhaustively detailed treatise mainly based upon the author's own research, and presents a new and independent approach to the chemical and mechanical processes of soils. As such, it is a timely contribution to the progress of soil science, and it may also prove to be the most notable world contribution yet made by Indian science. Dr Puri's own preface rejects the description of his book as a treatise, and insists that it is written for students. It is difficult to accept this, for his conceptions are unorthodox, and, although they simplify the problems of soil science for students, they must obtain general approval before they can be regarded as safe foundations for education.

No one could disagree with Dr Puri's contention that orthodox soil science is confusing, incomplete, and all too often indecisive. He pleads, with both eloquence and evidence, for simpler and more fundamental principles. If the best that our present principles can provide is soil analysis results which must be interpreted more or less empirically, is it not time to return to the beginning and reshape our ideas? Most younger soil scientists are increasingly conscious of these weaknesses, and they will find Dr Puri's attempt to unify the irreconcilables and close the gaps remarkably bold and stimulating.

His chemical approach to soils is they are all acids capable of forming salts; these salts are called 'saloids' and natural soils are mixtures of saloids of soil 'acidoids.' Their chemical behaviour follows ordinary stoichiometric laws. As saloids are salts of weak acids, they are considerably subject to hydrolysis; thus, dry regions will tend to have alkaline soils and areas of high rainfall acid soils. The author insists that soil investigations must be concentrated upon the exchangeable hydrogen of the soil acidoids. He rejects the conception of adsorption, particularly for the phosphate ion. He presents a purely chemical explanation for the nitrification of nitrites.

Whether all Dr Puri's simplifications will achieve eventual support remains to be seen. Many may feel that soil science, like medical science, must remain among the inexact sciences. It is, nevertheless, of the greatest importance that this book should be carefully studied by soil scientists.

D. P. HOPKINS

RICHARD WILLSTÄTTER

Richard Willstätter: "Aus meinem Leben." Edited by Arthur Stoll. Pp. 462, *with a coloured portrait and* 49 *illustrations. Verlag Chemie, Weinheim/Bergstrasse.* 1949. 28 DM.

When Richard Willstätter died in 1942, shortly before his seventieth birthday, one of the last great figures of organic chemistry in Germany had gone. It is an unbroken line of pioneers, leading from Justus von Liebig to his pupil A. von Kekulé, to Adolf von Baeyer, and to Emil Fischer and Richard Willstätter. Few belonging to Willstätter's generation are left; Willstätter's successor at the university of Munich, H. Wieland, is due to retire, and Hans Fischer, another of Munich's great organic chemists, is dead.

The memoirs of Willstätter, written for the most part in exile in Switzerland, have been carefully collected and edited by his faithful friend and assistant of many years, Arthur Stoll. His scientific work is treated merely as a sideline in this book, which is mainly a contribution to the cultural and scientific life of Europe. The distinguished career of Willstätter, which was begun in Munich under his great master, Adolf von Baeyer, led to the scientifically rich period at Zürich, and then to a few years in Berlin-Dahlem. It ended in 1924 when, once more in Munich—this time as Baeyer's successor—he voluntarily resigned, long before Hitler came to power, in protest against anti-Jewish discrimination. However, Willstätter continued his work on enzymes, with his faithful assistant Dr Margarete Rohdewald, until, in 1939, he found refuge in Switzerland from threatening and unbearable persecution.

This autobiography of a great scientist is written without bitterness, but with all the love of a good German for his country. Richard Willstätter, who was a Foreign Member of the Royal Society and a Nobel Laureate, will be remembered for his work on alkaloids, chlorophyll, anthocyanins, and enzymes when the nightmare names of his persecutors are long forgotten.

P. ROSBAUD

OCEANOGRAPHY

The Sea and its Mysteries, by John S. Colman. Pp. 285, *with various line drawings and half-tone illustrations. G. Bell and Sons Limited, London.* 1950. 12s. 6d. net.

The sea is a vast three-dimensional medium. The science of oceanography, of which it forms the subject-matter, is a composite of all the sciences from astronomy (through its connection with the tides) to bacteriology. Nowadays no one person can have detailed knowledge of more than a few of these sciences, and even the expert will in any case have either a physical or a biological outlook. It follows that any general account of the sea must reflect the major interests of the author. Mr Colman is a zoologist, as the reader of his book will soon discover, but he has produced an unusually well-balanced account of the sea. His initial chapters deal with the physics and chemistry, and while they naturally owe much to *The Oceans* by Sverdrup, Johnson, and Fleming, they also contain what is probably the first popular account of recent work on waves.

Mr Colman speaks with the authority of unusually wide experience when he comes to deal with marine biology. He has personally studied tropical plankton, worked on coral reefs of the Great Barrier of Australia and in the West Indies, has made important contributions to the study of intertidal zonation on both British and American shores, and has carried out deep-sea investigations in many latitudes. All this appears in his writing, which has a most refreshing—and in popular books a most unusual—air of first-hand knowledge. The book is illustrated with a series of excellent plates and many text figures. those dealing with deep-sea animals being particularly good. The reviewer considers this to be as good a book on the subject as could be written within its compass.   C. M. YONGE

CHEMICAL CALCULATIONS

Advanced Chemical Calculations, by S. J. Smith. Pp. 454. *Macmillan and Company Limited, London.* 1950. 17s. net.

This is intended to continue the author's 'Introductory Chemical Calculations' to intermediate and honours standard. Problems not lending themselves to comparatively easy mathematical treatment, or involving only substitution in formulae, are omitted. A very large number of examples, many from examination papers, with answers, will make the book useful to students

and teachers. In some cases the text explains the methods, in others reference is made to books. Calculations in organic chemistry are included, but methods of deducing structure are not explained. Thermodynamics and electrochemistry form part of the syllabus in physical chemistry. The American nomenclature and symbols are used in thermodynamics but the European convention for electrode potential in electrochemistry. The symbol °A is used instead of the now common °K, and the faraday is denoted by φ instead of F (its value being taken as 96,540, which corresponds to the old atomic weight of silver, 107·93). The text is usually adequate, although the difficult question of liquid contact potential, which causes trouble with most students, is not very well done, and some cases in which it occurs are treated as though it were absent. Some minor inaccuracies can be corrected in future editions. There is confusion between $\overline{u^2}$ and $\overline{u}^2$ in kinetic theory. The curves in figure 3, page 47, show maxima and minima of vapour pressure rather than deviations, and C_A, etc., on page 147 are not 'specific heats.' In the deduction of freezing point depression from the lowering of vapour pressure it is much better to deal with the ice curve than with the solution curve, as is done on page 325, since the good student will notice that no formula for the change of vapour pressure of a solution with temperature has been found. This book will be useful, and all teachers will agree that the working of numerical exercises is necessary in arriving at a real understanding of physical chemistry.

J. R. PARTINGTON

PLANT PATHOLOGY

Plant Pathology, *by Sir Edwin Butler and S. G. Jones, D.Sc. Pp. xii + 979, with 435 half-tones and line drawings. Macmillan and Company Limited, London. 1949. 63s. net.*

One of the few men having the breadth of experience and vision needed to scan the whole field of plant pathology was Sir Edwin Butler. In his earlier work, *Fungi and Disease in Plants*, published in India in 1918, a general section on fungal morphology, nutrition, and pathogenesis was followed by descriptions of diseases of oriental crop plants. The present volume was first undertaken as a revision of the 1918 text but developed into a completely new book, in which the emphasis on tropical plant diseases was transferred to those of importance in Britain.

Before his death in 1943, Sir Edwin had almost completed the general section of the work, which is distinguished by his assured handling of the relations between host and fungus, and of the influence of environment on parasitism. This section is concluded by a general survey of the disorders of plants caused by viruses and by nutritional deficiencies.

For the remaining two-thirds of the volume Dr S. G. Jones chooses the plan of marshalling specific diseases by crops, not by the systematic position of the pathogens. The diseases selected for description include not only those of cereals, pasture crops, roots, vegetables, and fruit, but of ornamentals and forest trees. The examples range over a wide geographic field, but prominence is given to the diseases common in Britain.

In a subject now so dissected by specialization it may well be that this book will represent a last attempt to produce a comprehensive text. By its very nature a synthesis of this type must have numerous faults in detail, but the whole remains an outstanding performance, demanding a place in every laboratory in which plant disease is studied. Its long-awaited publication crowns the great achievement of the senior author in shaping the course of plant pathology throughout the British Commonwealth and Empire.

R. W. MARSH

AERIAL MAPPING

Aerial Mapping and Photogrammetry, *by Lyle G. Trorey. Pp. 178, with numerous half-tones and line diagrams. Cambridge University Press, London. 1950. 25s. net.*

Dr Trorey has had a great deal of experience in the field of surveying from air photographs, and in consequence this most useful book is practical in its approach to the subject-matter. It is almost entirely restricted to work at topographical scales, and includes many descriptions and diagrams, particularly of the graphical methods employed in map-making. The modern automatic plotting machines are not entirely neglected, for the chapter dealing with Multiplex equipment is both informative and well written. Apparatus other than the Multiplex using the space intersection methods is, however, dealt with only very sketchily.

Information is given about the techniques used in Canada and not generally practised in this country. Of particular interest is that section dealing with oblique photographs.

The publication of such a volume is particularly appropriate now that so many changes in the methods of land surveying are being made. One is left, however, with the feeling that some considerable period elapsed between the completion of the original manuscript and the date of publication, for part of the information given relates to methods and apparatus that are no longer considered to be economically employable, at least from the commercial point of view of mapping from air photographs.

E. A. MISKIN

HIGH POLYMERS

High Polymeric Chemistry, *by W. S. Penn. Pp. 487, with various line and half-tone illustrations. Chapman and Hall Limited, London. 1949. 36s. net.*

This book on high polymers is one of several now appearing which aim at bridging the gap between technological treatises on plastics and physico-chemical monographs on long molecules. The Mark and Mark-Raff volumes in the Interscience series were the first general textbooks on the subject, and, more recently, Bawn and Ritchie in Britain have both written further general accounts of polymer chemistry.

Mr Penn's book comes closest to those of Ritchie and Mark-Raff in content, and is a qualitative account of the general and organic chemistry of high polymers. Good books can be written from this standpoint, as Ritchie has shown, but this is not one of them. Its chief and most curious characteristic is that it is up to date in its content yet out of date in its treatment. It certainly covers a wide range of polymer subjects, many of which, such as "cold" GR–S synthetic rubber, have only recently become of topical interest, but the treatment throughout is singularly old-fashioned, if not woolly. From the references, the book seems to have been written in the 1945–7 period, yet the ideas in it are more appropriate to 1940. The range of references, both academic and industrial, is extremely wide, and this perhaps explains the flavour of the book, because little attempt has been made to prune out many ancient, irrelevant, and discredited theories and experiments. This applies especially to the early and important chapters on mechanisms and methods, both of which are very disappointing. The book contains many wild generalizations which cumulatively are very irritating. I do not feel that it succeeds in its object.

R. F. TUCKETT

Some books received

AGRICULTURE

Agricultural Periodicals of the British Isles 1681–1900, and their Location, *Compiled by F. A. Buttress. Pp.* 16. *School of Agriculture, University of Cambridge.* 1950. 2*s. net.*

ASTRONAUTICS

Interplanetary Flight, *by A. C. Clarke. Pp.* 164, *with numerous half-tone and line illustrations. Temple Press Limited, London.* 1950. 8*s.* 6*d. net.*

ASTRONOMY

Astronomy of Stellar Energy and Decay, *by Martin Johnson. Pp.* 216, *with line and half-tone illustrations. Faber and Faber Limited, London.* 1950. 16*s. net.*

BIOLOGY

Amino Acids and Proteins—Cold Spring Harbor Symposia on Quantitative Biology. *Pp.* 217, *with numerous half-tone and line illustrations. The Biological Laboratory, Cold Spring Harbor, U.S.A.* 1950. $7 *net.*

Biochemical Aspects of Genetics, *edited by R. T. Williams. Pp.* 60. *Cambridge University Press, London.* 1950. 6*s. net.*

Biological Oxidation of Aromatic Rings —Biochemical Society Symposia No. 5. *Pp.* 96, *with various tables and line diagrams. Cambridge University Press, London.* 1950. 8*s. net.*

Wild Animals in Captivity, *by H. Hediger. Pp.* 207, *with numerous line drawings and half-tone illustrations. Butterworth's Scientific Publications, London.* 1950. 35*s. net.*

Mineral Nutrition in Plants and Animals, *by Frank A. Gilbert. Pp.* 131, *with numerous half-tone illustrations. Hutchinson's Scientific and Technical Publications, London.* 1950. 12*s.* 6*d. net.*

Unités Biologiques Douées de Continuité Génétique. *Pp.* 199, *with several half-tone and line illustrations. Éditions du Centre National de la Recherche Scientifique, Paris.* 1950. 1000 *francs.*

BOTANY

Iodine and Plant Life—Bibliography 1813–1949. *Pp.* 1111. *Chilean Iodine Educational Bureau, London.* 1950.

Plants and Vitamins, *by W. H. Schopfer. Pp.* 293, *with half-tones and line drawings. Chronica Botanica Company, Waltham, Mass., U.S.A.* 1950. $5 *net.*

The Propagation of Plants, *by E. J. King. Pp.* 264, *with numerous line diagrams. Hutchinson's Scientific and Technical Publications, London.* 1950. 16*s. net.*

CHEMISTRY

A Manual of Organic Chemistry for Advanced Students, *by G. Malcolm Dyson. Pp.* 984, *with various tables and line diagrams. Longmans, Green, and Company Limited, London.* 1950. 63*s. net.*

Organic Syntheses, Vol. 29, *edited by C. S. Hamilton. Pp.* 119. *John Wiley and Sons Inc., New York; Chapman and Hall Limited, London.* 1950. 20*s. net.*

The Physical Chemistry of Electrolytic Solutions (*second edition*), *by Herbert S. Harned and Benton B. Owen. Pp.* 645, *with various line diagrams. Reinhold Publishing Corporation, New York; Chapman and Hall Limited, London.* 1950. 80*s. net.*

Progress in Chromatography 1938– 1947, *by L. Zechmeister. Pp.* 368, *with half-tones and line diagrams. Chapman and Hall Limited, London.* 1950. 45*s. net.*

A Textbook of Inorganic Chemistry, *by J. R. Partington. Pp.* 996, *with numerous line diagrams. Macmillan and Company Limited, London.* 1950. 25*s. net.*

Trilinear Chart of Nuclear Species, *by William H. Sullivan. Art work by Kay Benscoter. John Wiley and Sons Incorporated, New York; Chapman and Hall Limited, London.* 1949. 20*s. net.*

The Friction and Lubrication of Solids, *by F. P. Bowden and D. Tabor. Pp.* 337, *with numerous half-tones and line illustrations. Oxford University Press, London.* 1950. 35*s. net.*

GENERAL SCIENCE

The British Journal for the Philosophy of Science (Volume I, No. 1). *Editor: A. C. Crombie. Pp.* 76. *Thomas Nelson and Sons Limited, London.* 1950. 7*s.* 6*d. net.*

Great Men of Science, *by Philipp Lenard* (reissue). *Translated from the second German edition by H. Stafford Hatfield. Pp.* 389, *with numerous half-tone illustrations. G. Bell and Sons Limited, London.* 1950. 15*s. net.*

Science News No. 16. *Edited by J. L. Crammer. Pp* 176, *with several half-tone and line illustrations. Penguin Books, London.* 1950. 1*s.* 6*d. net.*

INDUSTRY

The Paint Industry in Germany during the Period 1939–1945, *by Neil R. Fisk and H. W. Bowron. Pp.* 153, *with halftones and line diagrams. British Intelligence Objective Sub-committee Surveys Report No.* 22. *H.M. Stationery Office, London.* 1950. 3*s. net.*

MEDICINE

Medicine in 1850 (Catalogue of an Exhibition). *The Wellcome Historical Medical Museum. Pp.* 64, *with several half-tone illustrations. Oxford University Press, London.* 1950. 3*s. net.*

PHYSICS

The Acceleration of Particles to High Energies. *Session arranged by the Electronics Group. Pp.* 58, *with numerous half-tone and line illustrations. Institute of Physics, London.* 1950. 10*s.* 6*d. net.*

Atomic Energy, *edited by J. L. Crammer and R. E. Peierls. Pp.* 200, *with several half-tones and line diagrams. Penguin Books, London.* 1950. 1*s.* 6*d. net.*

An Introduction to the Luminescence of Solids, *by Humboldt W. Leverenz. Pp.* 569, *with numerous line diagrams. John Wiley and Sons, New York; Chapman and Hall Limited, London.* 1950. 96*s. net.*

Pocket Encyclopaedia of Atomic Energy, *by Frank Gaynor. Pp.* 204, *with various line diagrams. The Philosophical Library, New York.* 1950. $7.50 *net.*

Practical Applications of Spectrum Analysis, *by Herbert Dingle. Pp.* 245, *with several half-tones and line diagrams. Chapman and Hall Limited, London.* 1950. 40*s. net.*

Structure of Molecules and the Chemical Bond, *by Y. K. Syrkin and M. E. Dyatkina. Pp.* 509, *with line and half-tone illustrations. Butterworth's Scientific Publications, London.* 1950. 63*s. net.*

Elementary Pile Theory, *by Harry Soodak and Edward C. Campbell. Pp.* 73, *with several line diagrams. John Wiley and Sons, New York; Chapman and Hall Limited, London.* 1950. 20*s. net.*

ZOOLOGY

Australian Journal of Marine and Freshwater Research, *edited by N. S. Noble.* (*Vol.* 1, *No.* 1). *Pp.* 154, *with numerous half-tones and line illustrations. Commonwealth Scientific and Industrial Research Organization, Melbourne.* 1950. 7*s.* 6*d. net.*

Notes on contributors

E. N. DA C. ANDRADE,
D.Sc., Ph.D., F.R.S.,

Was born in London in 1887 and was educated at St Dunstan's College, the Universities of London, Manchester, and Heidelberg, and the Cavendish Laboratory at Cambridge. In 1928 he was appointed Quain Professor of Physics in the University of London. He served as an artillery officer in France in the war of 1914–18, and afterwards was for some years professor at the Artillery College (later the Military College of Science). At University College he established a flourishing school of physics, known for fundamental work on the mechanical properties of the solid and liquid state, but his laboratories were completely destroyed by bombs in September 1940. Since 1st January, 1950, he has been Director in the Royal Institution of Great Britain and Director of the Davy-Faraday Research Laboratory. He has a well-known collection of early books on the exact sciences, and is an expert on Newton and his contemporaries. He maintains close connection with continental colleagues, and was recently elected *Correspondant de l'Académie des Sciences*. He is known for the clarity of his exposition of science both in writing and by lectures. His interests are wide and varied, ranging from the history of science to art, poetry, and music.

SIR CYRIL (SANKEY) FOX,
D.Sc., F.G.S., F.R.A.S.B.,

Was trained to be a civil engineer, but took a degree in mining at the University of Birmingham in 1908. He was at Cannock Chase collieries in 1908–9, and was then lecturer in mine surveying at the University of Birmingham from 1909 to 1911, when he joined the Geological Survey of India. He served as Brigade Signal Officer (Royal Engineers) in the 15th (Scottish) Division in France until 1917 and was then sent to assist in mineral development in India with the Geological Survey of India. Besides serving in all parts of India, he has been on duty in Abyssinia, Afghanistan, Nepal, Burma, and the U.S.S.R. He has also served in Arabia. He was knighted for his war services as Director of the Geological Survey of India, for mineral exploration (1939–43). He has written numerous papers on economic geology, including memoirs on Indian coal, a book on bauxite, a treatise on engineering geology, and a work on the geology of water supply. He specialized on water-supply problems and all aspects of economic geology, particularly in exploratory surveys and in a consultant capacity.

E. FAURÉ-FREMIET

Was born in 1883 in Paris, where he graduated at the Sorbonne. A pupil of (1904), and assistant to (1910), L. F. Henneguy at the *Collège de France*, he succeeded him in 1928 in the chair of comparative embryology. His principal researches have been on infusoria, a field in which he has published numerous original papers.

H. GRAHAM CANNON,
M.A., Sc.D., D.Sc., M.Sc., F.R.S.,

Was born at Wimbledon, Surrey, in 1897, and was educated at Wilson's Grammar School, Camberwell, and Christ's College, Cambridge. After a short spell in the Ministry of Fisheries in 1918, he returned to Cambridge for a year to work under Doncaster. He then went to the Imperial College and, in 1926, was appointed to the chair of zoology in the University of Sheffield. In 1931 he was invited to the University of Manchester, where he has been ever since. He is a functional morphologist whose interests lie among the *Crustacea*.

S. TOLANSKY,
Ph.D., D.I.C., D.Sc., F.R.A.S.,

Was born in 1907 at Newcastle-on-Tyne, where he first graduated. He then studied in Berlin and London. Appointed to the staff of the physics department of Manchester University in 1934, he remained there and became reader in physics in 1945. In 1947 he was appointed to the chair in physics at the Royal Holloway College, London University. He is author of numerous papers on spectroscopy and interferometry, and of four books. During the war he carried out spectroscopic investigations for the atomic bomb project. For the past eight years he has developed new interferometric techniques for the study of surfaces, and for this work was awarded the Charles Vernon Boys prize by the Physical Society of London.

J. N. ALDINGTON,
B.Sc., Ph.D., F.R.I.C., F.Inst.P., F.I.E.S., A.M.I.E.E.,

Was born in 1905 and was educated at the Balshaws Grammar School, Leyland, the Harris Institute, Preston, and the Technical College, Blackburn. He has been with Siemens Electric Lamps and Supplies Limited since 1923, and is now a Director of the Company and Director of Research and Deputy Works Manager. He is the author of various papers and articles dealing particularly with developments in electric discharge lamps, and has twice been awarded the Leon Gaster Memorial Premium for theses on fluorescent light sources and their applications and on bright light sources. He is chairman of the Light Sources Secretariat of the National Illumination Committee, and in 1949 he was appointed president of the Illuminating Engineering Society of Great Britain. In 1950 he was made president of the Preston Scientific Society and appointed a governor of the Grammar School, Preston.

K. R. WEBB,
B.Sc., Ph.D., A.R.I.C.S.

Lecturer in chemistry, University College, Southampton, since 1939, and vice-warden of Connaught Hall there since 1945. Formerly part-time demonstrator in inorganic chemistry, Leeds University, 1937–9. Born 1915, educated at St. Mary's R.C. elementary school, the High Pavement School, and University College, Nottingham, and worked there with (the late) Dr E. B. R. Prideaux on derivatives of hydrogen fluoride (1935–7). Has published work on inorganic and physical chemistry, and articles and notes on historical and biographical topics, scientific and antiquarian. Local representative of The Chemical Society for the Southampton area since 1946.